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Energy recovery from wastewaters with high-rate anaerobic digesters

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ABSTRACT

Biodegradable wastewaters contribute as much as 6% of all anthropogenic methane emissions. High-rate anaerobic digesters have the potential to treat such wastewaters efficiently as well as enable capture of methane for use as a relatively clean energy source.

This paper traces the evolution of high-rate anaerobic digester technology and provides an overview of its present capabilities. It also makes out a case for an accelerated shift from energy-intensive aerobic processes to anaerobic processes which are not only more energy-efficient but enable global warming control by methane capture.

Contents

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1. Introduction

An estimated 1500 km^3/d of biodegradable wastewaters are generated across the world including domestic sewage and effluents from food and food processing, dairy, distillery, tannery, pulp and paper, aquaculture, and other biotechnological industries [390]. The effluents vary in strength from those with low chemical oxygen demand (COD $\leq$ 700 mg/l^{-1}) – also called 'graywaters' – to 'blackwaters' of higher CODs (of the order of 1500 mg/l^{-1}) and much stronger streams approaching CODs of 35,000 mg/l^{-1}. These wastewaters are anaerobic, except very low COD wastewaters, and keep generating methane till most of their biodegradable constituents get decomposed.

It is estimated that over 80% of the wastewaters generated across the world are not presently collected or treated [95]. A substantial portion – about 2 million m^3 – is discharged into waterways every year [391]. Apart from generating methane as they decompose, these wastewaters contribute to eutrophication and dead zone formation in oceans as well as wetlands. The impact is cumulative; at present dead zones have been estimated to affect about 245,000 km^2 of marine ecosystems, with far-reaching adverse consequence [16–18,22,24,75,76,95].

In developing countries, much of the untreated wastewater remains lying in open sewers, pits, latrines, or lagoons. For example, nearly 74% of China's domestic wastewater-based methane emissions are estimated to come from latrines, with the majority of wastewater generated in rural China being left untreated [391]. In India 60% of the population, or 700 million people, have no access to toilets [298], leaving them with no other option but to defecate in the open. Rural areas in other countries contribute another 325 million population equivalent of untreated night soil [298]. The largest share of the methane emissions of the world's two most populous countries – China and India – comes from latrines, with open sewers contributing a sizable amount as well. In many fast-growing towns and cities wastewater infrastructure is inadequate or outdated, if not missing altogether. For example, the city of Jakarta, with a population of 9 million, generates 1.3 million m^3 of sewage daily, of which less than 3% is treated [82,95,391]. The undervaluing of clean water by providing it at a very low cost often makes it unattractive to spend money in treating unclean water [288].

Even in developed countries sizable portions of sanitary wastewater are still treated by archaic technology such as the one involving septic tanks which generate copious quantities of methane. For example in USA about 25% of the sanitary wastewater is treated by septic tanks which leads to about 65% of methane emissions attributable to the wastewater from that country [395].

In wastewater treatment plants biodegradable components of the influent undergo decomposition much more rapidly than occurs in nature but it still contributes substantial methane emissions. This happens because when fed to treatment systems— which typically involve screening, grit removal, sedimentation, biological unit processes, secondary sedimentation, sludge handling/disposal, and disinfection – release of methane occurs in each stage till the biological oxygen demand (BOD) is drastically reduced towards the final stages. Depending on the nature, characteristics, and strength of the wastewater, lesser or larger number of unit operations and processes are employed. Anaerobic zones of varying thickness tend to develop in most of the stages of the treatment train, leading to methane emissions [4,12,13]. Especially during the process of stabilization and disposal of sludge, appreciable quantities of methane can be produced because, theoretically, 40–45% of the sludge is convertible to biogas [394].

According to the United States Environmental Protection Agency [395], wastewaters accounted for more than 6%, or approximately 450 million metric tonnes of CO_2 equivalent

Table 1
Country-wise forecast and historic emissions of CH_4 from wastewater (as million tons of CO_2 equivalent) as per USEPA [395].

	1990	1995	2000	2005	2010	2015	2020	2025	2030
China	114.0	120.7	125.4	128.8	132.0	135.1	137.4	138.4	138.1
Nigeria	35.7	40.4	45.5	50.8	56.2	61.8	67.4	72.9	78.2
Mexico	15.5	22.3	28.7	29.6	31.4	33.1	34.7	36.3	37.7
United States	23.5	24.8	25.2	24.3	25.1	26.3	27.6	28.9	30.2
Indonesia	17.9	19.5	21.1	22.6	24.0	25.2	26.4	27.5	28.5
Russia	25.0	15.3	17.3	21.1	22.0	21.4	20.8	20.2	19.6
Bangladesh	10.6	11.8	13.0	14.0	15.0	16.0	17.2	18.3	19.4
India	8.2	9.0	9.8	10.7	11.5	12.2	13.0	13.7	14.3
Turkey	5.8	6.3	6.9	7.4	7.9	8.4	8.9	9.2	9.6
Argentina	4.3	4.7	5.5	5.8	6.1	6.5	6.7	7.0	7.3
South Korea	6.2	6.5	6.8	6.9	7.0	7.1	7.1	7.1	7.1
Burma	4.1	4.5	4.8	5.2	5.5	5.7	6.0	6.3	6.5
Iraq	1.9	2.0	2.3	2.7	3.0	3.4	3.8	4.1	4.5
Peru	2.6	2.9	3.2	3.4	3.6	3.8	4.0	4.2	4.4
Brazil	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.8	4.0
Rest of the world	**76.4**	**79.5**	**82.5**	**88.9**	**96.2**	**103.2**	**109.7**	**116.1**	**122.0**
World total	**354.2**	**372.9**	**400.9**	**425.3**	**449.8**	**472.7**	**494.4**	**514.0**	**531.4**

Table 2
Global anthropogenic CH_4 emission by all wastes—soil, liquid, and gaseous [395].

	$MtCO_2e$	% CH emission from all wastes
Landfilling of solid waste	799.0	41.0
Wastewater and manure management	686.6	35.2
Stationary and mobile combustion	244.7	12.6
Biomass combustion	203.7	10.4
Other waste	15.3	0.8
Total	*1949.3*	*100*

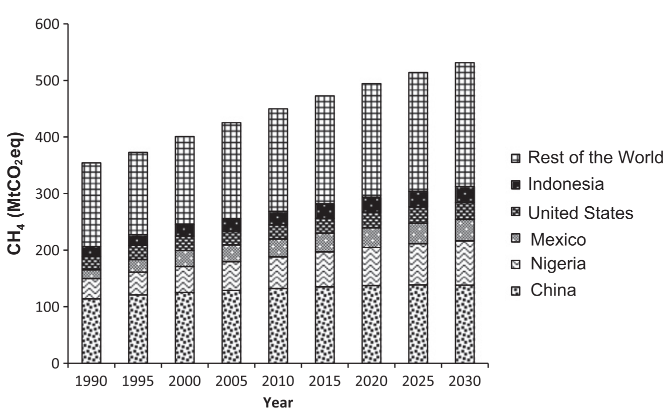

Fig. 1. Past, present, and projected methane emissions from wastewaters by the five biggest contributing nations and the rest of the world (adapted from Ref. [395]).

(MtTCO$_2$) of the estimated global anthropogenic methane emissions in 2010 (Table 1). These, together with manure management, represent 35% of methane emissions generated by all the wastes—liquid, solid, and gaseous (Table 2). China is by far the world's largest emitter of wastewater-based methane (Table 1), representing about 20% of the global methane flux. The past, present, and projected green house gas emissions from wastewaters are depicted in Fig. 1. The emissions have followed a sharply upward linear trend (Fig. 2). It must be emphasized that these calculations of global warming potential (GWP) of methane are based on the 2007 estimate of the Inter-governmental Panel for Climate Change [128] that each molecule of methane causes as much global warming as 25 molecules of CO_2. If a more recent estimates of Shindell et al. [345], according to which the GWP of CH_4 is 34 times that of CO_2, is used in the calculations, the figures

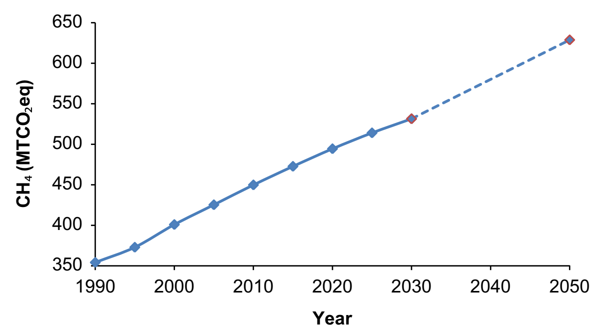

Fig. 2. Trends of global wastewater-based methane emissions (based on the data of [395]). The methane emission for the year 2050 is based on linear extrapolation by these authors.

of CO_2 equivalent would be 36% higher. Given the enormous, and rising, quantities of methane emissions that are involved it is imperative that steps are taken to capture that methane. Besides controlling global warming, generating a relatively cleaner source of energy, and improving public hygiene, these steps would also enable capturing plant nutrients (principally nitrogen, potassium, and phosphorous but also a host of micronutrients) which otherwise are not only wasted but become a major source of water pollution [1–3,13,19,23,26,404]. High-rate anaerobic digesters promise to facilitate such initiatives.

2. Aerobic and anaerobic wastewater treatment systems

Decomposition of biodegradable organic waste can occur both aerobically and anaerobically [145,352]. Both processes operate in nature, often together. For example a canal carrying sewage may have some dissolved oxygen present in its upper layer due to the effect of photosynthesis, atmospheric aeration, settling of particulates, etc. Aerobic decomposition would occur in that layer but deeper down where there is no dissolved oxygen, facultative and anaerobic bacteria would cause anaerobic decomposition [8–10,25].

In all engineered biowaste treatment systems also, decomposition is made to occur either aerobically or anaerobically [150,308,338,352]; each of the two routes have some distinctive features which are sought to be exploited in the treatment processes.

As do all other cells in living organisms, bacterial cells also try to achieve maximum cell growth for the least amount of energy expended. Under aerobic conditions free dissolved oxygen is the terminal electron acceptor. For each unit mass of substrate, as

measured by the biological oxygen demand (BOD) consumed, approximately 70% is used for cell growth and 30% for energy purposes [132,150].

Under anaerobic conditions, no molecular oxygen is present and the environment is a reducing one in contrast to the oxidizing state of aerobic conditions. The oxidation–reduction potential (ORP) values for anaerobic systems are approximately −490 to −550 mV [245] compared to +50 to +150 mV for aerobic systems. Under anaerobic conditions, carbon atoms associated with some of the organics become electron acceptors and are reduced, while other organics are oxidized to carbon dioxide and volatile acids [295]. This reaction results in end products that still contain large amounts of energy (i.e. the potential to accept electrons) in the form of methane. Cell reproduction is consequently lower under anaerobic conditions than aerobic conditions [295].

Aerobic processes operate most effectively over a range of pH 6.5–8.5. A well-mixed aerobic activated sludge system is a self-neutralizing process: first caustic alkalinity reacts with CO_2 generated by the biological reaction and yields bicarbonate. Volatile acids then biodegrade to CO_2 and H_2O and the CO_2 is stripped from the reactor. These steps keep recurring and no external neutralization is normally required.

In anaerobic processes, the methanogenic bacteria are pH sensitive and have a narrower optimum range of pH: 6.5–7.5 [91]. The pH must not be allowed to fall below 6.2 as it begins to impede the methanogenic bacteria. To ensure this, bicarbonate alkalinity should be kept in the range of 2500–5000 mg/l. The resulting buffer capacity is adequate to handle the impact of volatile fatty acid formation. Bicarbonate is usually employed to control alkalinity and pH in anaerobic reactors.

For most wastewaters, the net sludge yield from aerobic activated sludge treatment is of the order of 0.5 kg of volatile suspended solid (VSS) per kg COD removed. In contrast, the sludge yield from anaerobic treatment is less than 0.1 kg VVS/kg COD removed [248]. As anaerobic bacteria contain approximately the same cell composition as all other types of bacteria, they require nutrients in the same proportions as aerobic bacteria do to enable good cell growth. Nitrogen and phosphorus quantities added to the system need to be approximately 8–12% and 1.5–2.5%, respectively, of the change in total cell mass.

Table 3 summarizes the advantages and disadvantages of anaerobic and aerobic systems.

3. Low-rate and high-rate anaerobic digesters

As recounted recently [27] the classical unstirred and semi-continuous anaerobic digesters – of which 'biogas' digesters used in rural India, China, and other developing countries are examples–are 'low-rate' in the sense that it takes 4–6 weeks for the biodegradable slurries to be significantly biodegraded in these systems. The septic tank and the lmhoft tank, used from the late 19th century to the present day to treat sewage in individual houses or small groups of houses, are also examples of low-rate anaerobic digesters.

Up to the mid-20th century, anaerobic digesters were considered too slow to be useful in treating wastewaters; there use was largely confined to stabilizing dairy animal manure [28]. The septic and the lmhoff tanks used for treating domestic wastewaters were rather crude and inefficient as digesters because they were based on the misconception that the settleable solids are the most important sewage component to be removed [252]. Due to this, their designs minimized sludge-water contact instead of maximizing it. The sewage flows through the upper part of these 'decanter digesters' while settleable solids are retained in the lower part where they undergo anaerobic digestion. In reality settleable solids account for only about 1/3 of the organic load in raw sewage; another 1/3 is present in the form of colloids and the remaining 1/3 as dissolved matter. In septic and Imhoff tanks most of the colloidal and soluble fractions are not biodegraded because the design of the tank is such that there is no possibility of continuous contact between the non-settleable fractions and the underlying sludge where bacteria are most active. As a result only 30–40% of organic material gets degraded in the tanks, that too over a course of several weeks. The poorly stabilized overflow reaching the dispersion trenches is highly putrid.

In the early decades of the 20th century high-rate aerobic processes were developed in which intimate contact was maintained between the microorganisms and the wastewater by brisk agitation [275]. A portion of exiting sludge was recycled to provide much higher concentration of microorganisms per unit wastewater flow in the main reactor compartment than would otherwise have

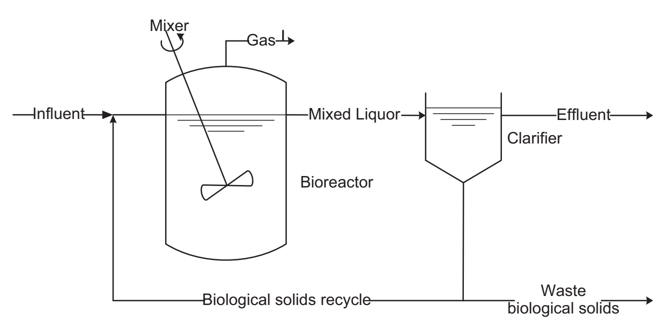

Fig. 3. The anaerobic contact reactor.

Table 3
A comparison of post-modern aerobic and anaerobic wastewater treatment processes [444,445].

Aspect	Anaerobic	Aerobic
Energy requirements	Low	Much higher
Extent of loading possible	High to very low	Moderate to very low
Degree of treatment	High (>90%)	(>95%)
Sludge production	Very low	Much higher
Process stability (to toxic compounds and load changes)	Good	Good
Startup time	2–4 weeks	2–4 weeks
Nutrient requirements	A fifth or lesser than aerobic processes	Higher than 5 times for certain industrial wastes
Odour problems	Low, as the systems are air-tight	Low, despite systems being largely open
Energy production	Yes	No
Nutrient recovery	Possible	Not possible
Effluent quality	Generally contains higher suspended solids and ammonical nitrogen; require aerobic 'polishing'	Relatively better stabilized and fit for discharge

Table 4
Illustrative examples of the use of anaerobic CSTR.

Type of feed	Volume of digester (m)^3	HRT (d)	Temperature (°C)	Loading rate (kg VS/m^{3}d)	Volatile solids (VS), utilization (%)	Biogas production, (m^3/kg) of VS	Methane (%)	References	Remarks
Piggery wastes	–	10	35	1.4–4.5	–	0.43	–	[406]	–
-do-	–	15	35	4.0	–	0.55		-do-	–
-do-	–	10–15	33	1.9–3.9	–	0.26–0.45	–	-do-	–
-do-	–	20	35	2.4–3.0	–	0.37–0.54	–	-do-	–
-do-	–	15	30	3.5	–	0.33–0.49	–	-do-	–
-do-	–	10–15	30	2.0–3.0	–	0.24–0.33	–	-do-	–
-do-	–	10–20	30	2.3–4.5	–	0.28–0.39	–	-do-	–
-do-	–	15–20	30	3.4–4.5	–	0.32–0.33	–	-do-	–
-do-	–	15	27–40	2.8	–	0.35–0.40	–	-do-	–
Fattening pig manure+straw and silage	60	22	33–38	5.0	–	0.49	60	-do-	Heating: internal serpentine coils Stirring: horizontal mechanical axle-motor
Dairy cattle manure+silage waste	32	15.3	34–40	5.6	33	014	56	-do-	Heating: External heat exchanger Stirring: gas recirculation
Distillery wastes	–	10	35	2.7	55	0.55	65	-do-	Heating: not necessary since temperature of feed was about 400 °C Stirring: gaslift
Liquid manure from cows, heifers, calves, (partly straw mixed) vegetable material	100	10.25	30.50	2.0–5.0	35–40	0.38–0.42	59–62	-do-	Heating: two external heat exchangers Stirring: internal propeller, installed in the central tube acting downwards centrifugal pump
Piggery wastes	18.6	10–15	–	6.0	–	0.47	70–71	[205]	–
Dairy manure+barley straw	0.13	25	35	5.2	29	0.84	65	[169]	Heating: circulation of hot water in a jacket surrounding the unit
	0.13	20	35	6.5	28	0.93	64	-do-	
	0.13	15	35	8.7	26	0.96	61	-do-	
	0.13	10	35	12.5	24	0.83	58	-do-	
Primary sludge	–	17	35	1.4	–	0.37	68	[88]	–
Macrocystispyrifera (raw kelp)	2[a]	18	35	1.6	50.8	0.478	58.2	-do-	Heating: keeping the digester at const. temp. chamber stirring: intermittently (15 min h^{-1}) by a magnetic stirrer at 130 rpm
-do-	2[a]	10	35	1.6	38.6	0.37	58.8	-do-	-do-
Baseline treated kelp	2[a]	10	35	1.6	35.6	0.35	59.3	-do-	-do-
-do-	2[a]	18	35	1.6	36.2	0.35	59.8	-do-	-do-
Baseline treated kelp juice (4:1)	2[a]	18	35	1.6	35.6	0.40	58.7	-do-	-do-
-do-	2[a]	10	35	1.6	24.0	0.32	64.1	-do-	-do-
(3:2)	2[a]	18	35	1.6	42.0	0.35	60.3	-do-	-do-
-do-	2[a]	10	35	1.6	23.3	0.18	66.1	-do-	-do-
Raw kelp (without nutrient) (with nutrient)	2[a]	12	35	1.6	45.1	0.14	57.8	-do-	-do-
	2[a]	12	35	1.6	42.6	0.39	59.8	-do-	-do-
Cow manure	35	15	–	–	–	0.28[b]	55	[182]	–
-do-	35	10	–	–	–	0.21[b]	60	-do-	–
Cattle manure	10	24	35	2.5–2.8	–	0.20–0.25	60	[161]	-do-
Screened dairy manure	0.003	16	22	2.1	12.2(3.3)[c]	1.124	63.5	[241]	–
-do-	0.003	15	22	1.9	13.8(2.9)[c]	0.149	64.6	-do-	–
-do-	0.003	12	22	2.9	11.8(3.4)[c]	0.112	63.5	-do-	–
-do-	0.003	10	22	2.8	14.3(2.8)[c]	0.102	64.6	-do-	–
-do-	0.003	10	22	2.9	13.8(2.9)[c]	0.115	62.7	-do-	–
Water hyacinth+sewage sludge	–	8–31	–	1.6–6.4	–	–	0.25	[164]	–
Brown algae *Laminaria hyperborean*	10	24	35	1.7	–	0.53	52.8	[162]	Heating: fitted with an automatic temp. control stirring: agitation system with continuously adjustable sped, stirring for 10 min. every 2 h Process: semi continuous, feeding once a day

Laminariasaccharina	10	24	35	1.7	–	0.45	51.1	-do-	-do-
Ascophyllumnodosum	10	24	35	1.8	–	0.22	50.0	-do-	-do-
POME	0.015	14	32	3.2[d]	50.8[d]	0.19	53	[276]	–
-do-	-do-	21	32	2.1[d]	50.6[d]	0.25	56	-do-	–
Petro chemical industry wastewater (DMT)	2.51	10	35	3.3[e]	–	–	–	[339]	–
Mixed wastewater from the cheese-processing industry	.0015	0.45	36.2	10.2[e]	–	–	53.9	[177]	–
Palm oil mill effluent (POME)	7500	18		2.6–3.5[d]		28.3 m^3 per m^3 of POME digested	54–70	[383]	A total of 1400 t of methane is captured and utilized as boiler fuel annually.
Cassava ethanol wastewater	0.005	5	55 ± 1	14[d]	–	0.20–0.25	55–61	[234]	–
olive mill wastewater and liquid cow manure	0.00075 and 0.004	19	35 ± 0.2	5[e]	–	–	65–74	[100]	Experiments were carried out in two CSTR reactors, one used for acidogenesis and the other for methanogenesis.
Tequila vinasses	0.04	5	35 ± 1	6[d]		0.537	> 60	[254]	

[a] Volume of digester 2 dm^3, semi-continuous.
[b] At standard conditions, 20 °C and 1 atm.
[c] Value given in the parenthesis are VS (%) in the feed.
[d] As COD.
[e] COD g/l.

been possible. Very brisk agitation, liberal aeration, addition of nutrients to support vigorous microbial activity – all augmented with sludge recycle – made high-rate aerobic decomposition processes such as the aerobic activated sludge process (AASP) highly time-efficient. They were also quite robust. As energy conservation and global warming were of little concern during all but the last three decades of the 20th century, aerobic processes dominated the global wastewater treatment scene [259].

The speed and efficiency of treatment achieved in these systems generated a misconception that it had to do with a higher metabolic capability as well as resilience of aerobic bacteria compared to the strict anaerobes which are involved in methanogenesis [403]. This misconception, that methanogens are slower than aerobes, and more susceptible to toxicity, persists in many quarters even today despite the development of anaerobic reactors which are even faster and sturdier than the most efficient of aerobic activated sludge processes [28].

4. Initial attempts to enhance the efficiency of anaerobic digesters

In the 1950s Morgan and Blodgett [268], and Torpey [384], introduced intense mechanical mixing in anaerobic reactors to make them confirm to the continuously stirred tank (CSTR) reactor hydraulics [392,393]. This improved the digester efficiency 2–3 fold in comparison to unstirred or intermittently stirred 'low-rate' digesters. Still, hydraulic retention times (HRTs) of 10–20 days were needed to achieve significant biodegradation compared to 6–16 h taken by the aerobic activated sludge process (AASP) and its variants.

In low-rate digesters the microbial population gets washed out of the reactor along with the effluent. Even the anaerobic CSTRs suffer from this drawback. It was felt that if the microbial wash out can be prevented, in other words if the solids retention time (SRT) can be enhanced even as HRT is lowered [21], it will lead to the presence of greater concentration of microorganisms in the reactor, thereby making the digestion much more efficient. To achieve this objective, anaerobic contact reactor was introduced in which a part of microbial population from the effluent stream was separated and was recycled back into the reactor (Fig. 3). This concept was borrowed from the AASP and was developed further by Schroepfer et al. [330], Schroepfer and Ziemke [328,329], and others. In 1961 Steffen and Bedker [354] set up a full-scale plant based on the anaerobic contact process for treating meat packing waste at a loading rate of 2.5 kg of BOD m^{-3} d^{-1}; with hydraulic retention time of 13.3 h. It achieved a BOD removal efficiency of 90%.

The primary disadvantage of the anaerobic contact process was the need for a degasifier in order to recycle reactor effluent solids; this played a role in limiting the appeal of the process. The anaerobic CSTR and the anaerobic contact process (which was basically an anaerobic activated sludge process) are sometimes referred as 'first generation' high-rate anaerobic digesters. Examples of use of CSTR and anaerobic contact reactor for wastewater treatment are given in Tables 4 and 5, respectively.

5. The second generation anaerobic digesters

5.1. The anaerobic filter

The concept of anaerobic filter (AF) was initially articulated by Coulter et al. [97] but the first demonstration of the potentially high efficiency of anaerobic wastewater treatment systems came from Young and McCarty [433], who successfully operated an upflow anaerobic filter, treating rum distillery wastewater. In their reactor (Fig. 4) a portion was filled with coarse gravel to

Table 5
Example of waste treatment by anaerobic contact reactors.[a]

Type of waste	Waste strength (g/l)	Suspended solids (g/l)	Reactor volume,(l)	Reactor temperature, (°C)	Loading rate, (g/l d)	Conversion (%)	References
Meat-packing waste	1.5 (TVS)	0.8	22×10^6	35	1.4–3.6	92–98	[331]
-do-	1.4 (TVS)		6–60	35	5–2	68–80	[328,329]
-do-	1.7 (TVS)	0.8	2.6×10^6	35	3	64	[355]
Bean-blanching waste	20 (COD)	<5	30	35	6.6	80	[400]
Potato-peeling waste	38.4 (COD)	<8	30	35	2.4	70	-do-
Synthetic sewage sludge	55 (COD)	47	30	35	10	78	-do-
Dairy waste	3 (COD)	–	14×10^3	35	1–2.5	55–70	[407]
Cannery waste	20 (COD)	<5	5×10^6	36–38	3	95	[74]
Sugar-beet waste	4.7 (COD)	<0.5	40	35–37	12–24	86–89	[250]
Edible oil refinery waste	–	–	3×10^{-3}	–	–	–	[171]
Acid water from edible oil refiner	–	–	0.5 m^3	–	–	–	[110]
Beef processing plant wastewater	2.7 (COD)	2.3	10 m^3	–	2–3	91.1	[207]
Ice cream waste water	–	5.8	–	–	1.7	63	[315]
Cheese whey	60–80 (COD)	–	6	37	30	86	[291]
Evaporator condensate from a sulphite pulp mill (lime used as neutralizer)	14.4 ± 0.5 (COD)	80	5500 m^3	–	$10.6\pm.71$	96.3	[72]
Potato-chips, maize chips and other snacks	5.2–5.7 (COD)	2.2–2.3	33	55	0.6 to 8	86–97	[334]

[a] Results are based on COD, BOD, or total volatile solids (TVS). Loading rates are typically the highest reported or achievable. Loading rates and conversions are given in COD, BOD or TVS depending on units for waste strength.

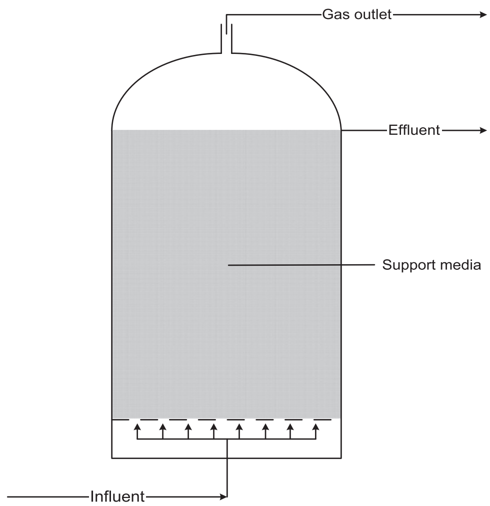

Fig. 4. The anaerobic filter.

provide a support media for the bacterial films to attach themselves. The influent was introduced from the bottom, and had an upflow pathway which guaranteed intense contact between the influent and the bacterial mass that was attached to the support media. The system enabled digestion in terms of COD removal to the extent of more than 10 kg/m^3d, which had not been possible even with the most advanced aerobic systems [87]. This showed that the poor performance of the earlier anaerobic digesters was not because of the 'slowness' of the anaerobic bacteria but was due to poor reactor design.

The performance of the AF has since been tested on a variety of wastewaters. This includes landfill leachate, high strength acid wastewater, wheat starch-gluten plant waste, pharmaceutical waste, shellfish processing waste, food processing waste, and organic particulates [59,62,84,131,155,292,300,365,423]. Medium as well as high strength wastes (1000 mg/l or greater COD) have been successfully treated. Table 6 provides illustrative information on the reach and the efficiency of the AF.

The success of the anaerobic filter brought to the fore two major advantages of anaerobic digestion not possessed by aerobic processes. The first is that anaerobic digestion produces methane which, if captured, is a source of clean energy. Due to this virtue anaerobic processes are much less *net* energy consumers than aerobic processes [28]. The second virtue is generation of more stable and less watery sludges which are much more easily disposable than aerobic sludges [27]. Soon the success of Young and McCarty [433] with the AF was to inspire a string of breakthroughs leading to novel high-rate anaerobic digesters which, together with AF, are also referred as the 'second generation anaerobic digesters' [28].

5.2. The downflow stationary fixed film (DSFF) reactor

This reactor was developed to avoid the problems faced by the AF due to the accumulation of solids in the packing material and the consequent plugging. The reactor contains solid packing similar to AFs but is operated in the downflow mode: the waste enters from the top and flows downwards (Fig. 5). There is dispersion of the down flowing waste by the gas produced in the reactor which is flowing upwards; this facilitates biodegradation [114]. Not only the formation but also the stability of an active biomass film on the surface of the support material of the reactor is an essential prerequisite for the successful operation of DFSFF reactors [106,272,399].

DFSFF reactors are capable of treating a wide variety of wastes from reasonably diluted to concentrated ones [106,192–194,337]. Table 7 illustrates the types of wastes which have been successfully treated by DFSFF reactors.

5.3. The upflow anaerobic sludge blanket (UASB) reactor

The UASB process was developed in the 1970s by Gatze Lettinga and coworkers at the Wageningen University [230]. Lettinga's team was experimenting with an anaerobic filter and they had observed that in addition to the biomass that was attached on the support material, a large proportion of the biomass had developed into free granular aggregates. Soon thereafter, in another reactor, Lettinga observed that its sludge was developing into compact granules. It made him believe that support material for biomass attachment was not necessary to retain high levels of active sludge in the reactor, and that this objective can be better achieved by developing granules which support active biofilms and possess good setting characteristics.

Table 6
Illustrative examples of treatment of different types of wastewaters achievable by anaerobic filter.

Type of feed	Volume of digester (l)	Filter media	HRT, (d)	Temperature (°C)	Loading rate (kg COD m^3/d)	COD reduction (%)	Biogas production (m^3/kg COD)	Methane (%)	References
Piggery waste	200	–	2–8.5	26–30	3.74–15.65	–	–	–	[77]
Silage effluent	8.4	Lime stone chips	3	28–30	4.7	76	0.49[a]	84	[52]
Water hyacinth + bermuda grass + MSW	6.4	Plastic raschig rings	5.2	35	6.1	94	0.60[b]	68	[140]
Cane molasses stillage	8.1	–	9	–	7.0	50–70	–	–	[366]
-do-	–	–	1–10		1–10	80–95	–	–	[398]
Sows and weaness manure	3500	Plastic matrix	5.5	25	3.7–4.7	66	0.26	86	[108]
Pig slurry	18	Clay, coral, mussel shells, plastic	6	33 ± 2	5	69–73.3	0.39–0.46[b]	85–87	[422]
Sulphite pulp mills	10	–	6.2	–	0.44	69	–	–	[137]
-do-	10	–	4.5	–	0.63	79	–	–	-do-
-do-	10	–	2.1	–	1.3	90	–	–	-do-
Pig slurry supernatant	3500	Polypropylene cascade mini rings	6	25	2.2	66	0.26	86	[423]
-do-	3500	-do-	6	25	4.3	66	0.26	86	-do-
-do-	3500	-do-	3	25	8.4	52	0.2	87	-do-
-do-	3500	-do-	3	35	9.9	60	0.25	87	-do-
Distillary water + water (1:1)	9	Stone rubble	30	24.5–31.0	2.05	77		72	[130]
-do-	9	-do-	20	24.5–31.0	3.02	74	–	65	-do-
-do-	9	-do–	15	24.5–31.0	3.46	62	–	60	-do-
Raw distillery water	9	Stone rubble	30	24.5–31.0	3.56	72	–	65	-do-
-do-	9	-do-	20	24.5–31.0	5.74	60	–	63	-do-
-do-	9	-do-	15	24.5–31.0	6.81	55	–	59	-do-
Mining wastewater	1.0	Dolomitic pebbles	20 h	3.3	–	–	–	–	[249]
Cattle slurry	20	Filter- pak CR 50 rings	5–14	35	–	–	0.26	–	[292]
Molasses wastewater	1.0	Pumice stones	35	10.0	15		–	–	[170]
Olive mill wastewater	115	Poly- ur*eth*ane foam	2	–	6	65–70	–	–	[317]
Swine slurry	15	Wood chips, PVC,	4.5	30	1.9	–	212	72	[349]
		clay	4.5	30	3.1	–	144	77	-do-
			4.5	30	1.4	–	32	68	-do-
Water hyacinth	73.63	–	10	28–30	–	–	130	64	[107]
Olive mill effluent	–	–	2.1	–	40	70–80	–	–	[39]
Date-processing industry waste	–	Plastic pipes	–	–	1.6–25	90	0.4–0.53	–	[62]
Palm oil mill effluent	230	–	15–6	–	1.2–11.4	90	20–165[c]	60	[64]
Tuna- processing waste	1	PVC raschig rings	4–1	37	11–13	75	–	–	[408]
Sea food processing wastewater	–	–	6.6	–	1.3	65	–1.3	–	[299]
Dairy waste	4300	Polypropylene raschig rings	24–40 h	35–37	9	70	–	–	[265]
Synthetic wastewater	0.9	Plastic tubes	3–9	20	0.27–0.82	81–90	54–78	–	[159]
-do-	–	Fire expanded clay pellets	1.1	–	–	92.8	6.4[d]	–	[85]
-do-	–	-do-	2	–	–	74.1	2.13[d]	–	-do-
Distillery wastewater	1	Nonwoven fabric material containing pyridinium group	1.6	53	18	80	–	50–53	[370]
Cassava starch extraction wastewater	9.46	Bamboo pieces	9.5 h	30–19	11.8	87	0.36	69–81	[93]
Municipal wastewater	17	Burnt brickbats	12 h	Winter 10–30 Summer 20–42	0.0333	97	0.35	60–70	[59]
Papermill wastewater	1.77	Rashing rings	6	55	12.25 ± 0.33	–	0.291 ± 0.02	60–70	[430]
-do-	-do-	-do-	-do-	35	11.38 ± 0.32	–	0.274 ± 0.02	-do-	-do-
Purified terephthalic acid	10	Honeycomb type media made of polystyrene	50–75 h	37	5.05	79	–	–	[184]
Poultry slaughterhouse wastewater	6.4	Pleated PVC ring	12 h	29–35	0.77	67	18.4[d]	42	[302]

h, HRT in terms of hours.

[a] Gas yield per kg COD degradation.
[b] Gas yield calculated for STP.
[c] Gas yield in terms of dm^3/d.
[d] Gas yield in terms of litre per day.

As it is in an AF, in a UASB also the feed enters through the bottom of the reactor and flows upward through a 'sludge blanket' containing a sludge bed and overlying granules. This enables very efficient mixing of wastewater with the granules leading to rapid anaerobic decomposition of the feed. The biogas that is generated also facilitates mixing. The rising influent then passes through a gas–liquid–solid separation device (Fig. 6). This device separates solids (granules) from the liquid effluent and also separates gas bubbles from the effluent. Only the liquid effluent flows out of the reactor while the solid sludge moves back in the reactor and the gas is collected in the gas collector.

The main problem associated with AFs – plugging of the filters by the suspended bacterial growth – is largely overcome in the UASB. Since the active microbial biomass forms dense granules, which are highly settleable [21,27,29,322], higher concentration of active biomass is achievable per unit working volume of the digester than is possible with the AF. Due to this UASB can handle higher COD loading rates and provide adequate treatment at lesser HRTs than is possible with the AF (Table 6).

Since both the UASB and the AF are dependent on suspended growth for high performance, the same types of wastes are suitable to both (Tables 6 and 8). The key to a UASB reactor's performance is the quality of granules of its sludge [21,35,117,175]. While certain wastes result in a granular sludge quite readily (for example sugar-processing waste and wastes containing mainly volatile acids), other wastes develop this granular sludge slowly and some not at all. Hence this aspect constitutes the major challenge in the success of UASB

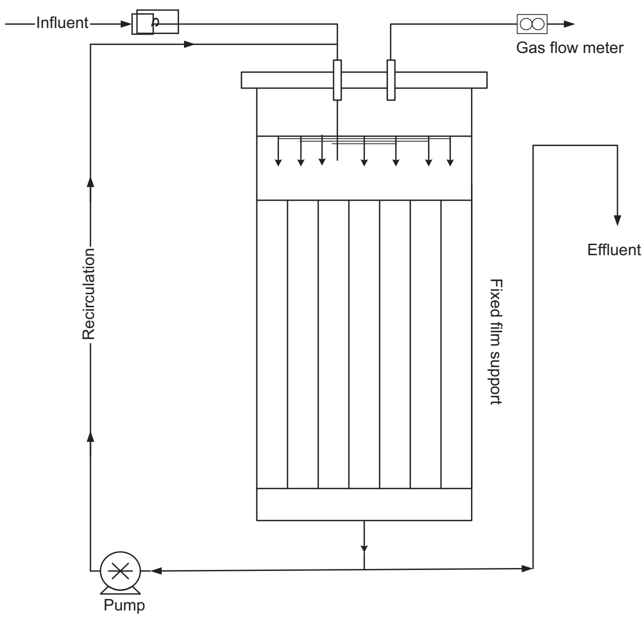

Fig. 5. The downflow stationary fixed film (DFSFF) reactor.

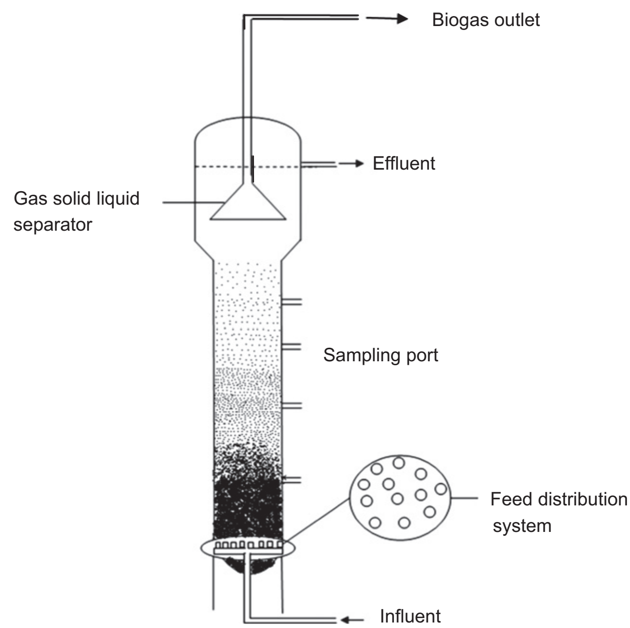

Fig. 6. The upflow anaerobic sludge blanket (UASB) reactor.

Table 7
Wastewater treatment with downflow fixed film reactors.

Type of waste	Waste strength (g/l)	Suspended solids (g/l)	Reactor size (l)	Reactor temperature (°C)	Loading rate ($g\,l^{-1}d^{-1}$)	Conversion (%)	References
Bean-blanching waste	5.5–22.0 (TVS)	<1	110	35	9.4	75	[357]
-do-	10 (COD)	1–3	0.7	10	4.2	88	[200]
Synthetic sewage sludge	55 (COD)	47	35	35	7.4–13.8	71–77	[401]
Chemical industry waste	14 (COD)	–	0.7	25	14	81	[200]
Piggery waste	27–51 (COD)	–	35	35	6.1–39.2	27–70	[195]
Pear-peeling waste	110–140 (COD)	43–55	35	35	6.4–18.9	58–54	[397]
Bean-blanching waste	–	–	–	35	18.2	88	[397]
Rum stillage waste	50–70 (COD)	4.5–6.5	35	35	13.3	57	[196]
Liquor from heat-treated sewage digester sludge	10.5 (COD)	<1	0.8–1.2	35	29.2	70	[196]
-do-	II (COD)	1	950	35	0–25	60	[156]
Rum stillage waste	70 (COD)	–	–	37–40	8–10	65–70	[367]
Fish-processing waste	6.20 (COD)	3–10	1.2	35	2.5–13	70–92	[115]
Sucrose waste	–	–	1.41	–	2–12[a]	88–96	[197]
Sucrose-based synthetic waste	–	–	22.4	35	5.33[a]	86.7	[113]
Synthetic medium	56–62[b]	–	1.4	37	10.5[a]	90–94	[71]
Dairy waste	–	–	–	–	5–15[a]	70–80	[198]
Tuna-processing waste	–	–	–	–	3[a]	70	[408]
Tuna processing wastewater	–	–	1	–	2–5[a]	70	-do-
Slaughter house waste	–	<1	3.75	20	9.2[a]	54–70	[106]

Results are based on COD, BOD, or TVS. Loading rates given are typically the highest reported or achievable. Loading rates and conversions are given in COD, BOD, or TVS depending on units used for waste strength.

[a] Loading rate in terms of kg/m^3 d.

[b] COD in kg/m^3.

Table 8
Illustrative examples of the applications of USAB reactors.

Type of feed	Volume of digester (m^3)	HRT (d)	Temperature (°C)	Loading rate (kg COD m^3/d)[a]	COD destruction (%)	Biogas yield (m^3/kg COD)	Methane (%)	References
Sugar-beet sap unsoured	0.064	1–2	30	4–5	95	–	–	[227]
Sugar-beet sap soured (closed circuit)	0.018	0.5–1	30	8–10	84–95	–	–	-do-
Sugar-beet sap soured (two-step)	0.018	1	30	8–9	97	–	–	-do-
Sugar-beet waste	–	0.7–2.1	25	5–8	95	0.47	83	[140]
Thermal sludge conditioning liquor	–	2	35	5.9	71	0.18[b]		[158]
Raw sewage	6	1–0.3	20	0.04	70–75	0.12–0.16	–	[147]
-do-	–	0.5–6	–	5–30	85–95	–	–	[398]
Paper mill effluent	70	2.5	–	9–9.5	70	0.41	70–80	[152]
Maize starch	800	0.8	40 15	15	90–95	180–200	–	[174]
Acid water from edible oil refinery	20	0.25	–	–	–	–	–	[313]
Sewage	3.7	10–18 h	24–26	660 mg/l	73	140	–	[277]
Row domestic sewage	35	5.2 h	23–24	0.43–0.52[c]	66	–	–	[326]
-do-	120[a]	4 h	19–28	0.627[c]	74	–	–	[51]
Domestic sewage	6	0.3	9.5–10	–	–	0.17–0.24	30–55	[229]
Glucose	3[a]	–	–	166.44 g/d	99.7	8.5 l/d	–	[287]
Cheese production	4	46 h	35	31[c]	90	–	––	[149]
Thermo- mechanical pulping wastewater	–	0.9 h	55	81	61	–	–	[312]
Methanolic waste	–	120	–	32[c]	70	–	–	[58]
Synthetic waste	5.5[a]	–	55	81	91	–	–	[387]
Slaughter- house waste	–	4–1.5 h	30	15	80–95	–	–	[325]
Domestic wastewater	1.2	–	> 12	–	60	300[d]	78	[61]
Synthetic coffee waste	–	24 h	> 55	4	> 75	–	–	[99]
Synthetic waste	1.7[a]	–	30	0.18–2	98	–	–	[411]
Synthetic waste	1.2[a]	–	–	13.8–39.6[c]	57.8–96.7	–	–	[341]
Sewage	67.5	–	–	–	80	–	–	[410]
Synthetic starch/sucrose waste	–	–	–	0.5[c]	75	–	–	[163]
Synthetic resin production wastewater	–	–	–	4.5	71	2.94[#]	–	[293]
-do-	–	–	–	4.5	78	3.5[#]	–	-do-
Low-strength wastewater with ethanol/whey	–	–	30	0.3–6.8[c]	95	–	–	[190]
Wastewater with formate	–	–	37	10–2029–65[c]	97–98 86–90	–	–	[86]
Malt whiskey wastewater	–	2.1	–	15	90	–	–	[143]
Tannery effluent	10[a]	12 h	–	–	70	0.15–0.25	80	[303]
Domestic wastewater	2[a]	4.6 h	20	3	53–76	–	–	[350]
Wheatstraw pulp black liquor	–	–	–	10	40–46	510[e]	–	[165]
Domestic wastewater	5 ml	–	–	–	75.3	0.15	75–80	[201]
Tannery wastewater	4[a]	5–7	29–34	1.5	39–50	0.1–0.3[d]l/d	–	[402]
Concentrated black (toilet) water	50[a]	8.7	25	1	93	10[d]	78	[102]
Palm oil mill effluent (POME)	1.5[a]		55					[126]

h, HRT in terms of hours.
[#]Biogas yield in terms of dm^3/dm^3 of wastewater per day.

[a] Volume of the reactor expressed as litres.
[b] As methane yield.
[c] Loading rate in terms of g COD/l d.
[d] Biogas yield in terms of l/d.
[e] Biogas yield in terms of 1 kg COD added.

technology. Inoculation with a large amount of granular sludge from a well-functioning UASB reactor often helps, but the problem is that even though the sludge granules retain their characteristics most of the time with a given type of waste, they are not necessarily able to do so when changing from one waste to another [280,420].

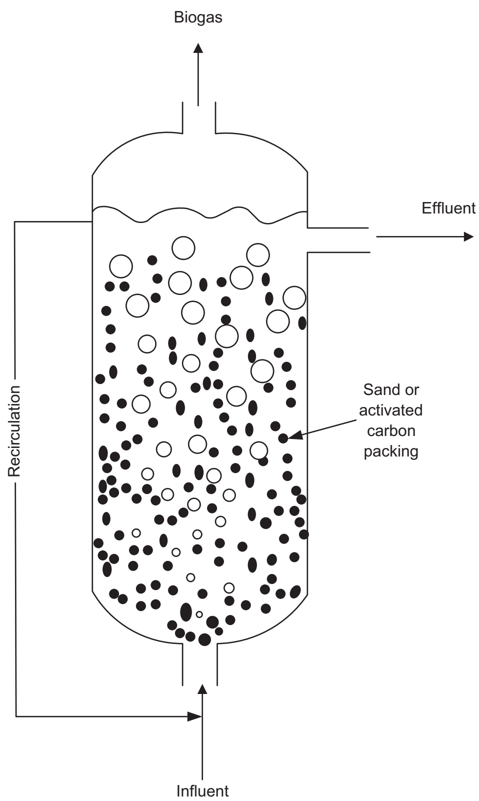

Fig. 7. The expanded-bed/fluidized bed reactor.

5.4. Anaerobic fluidized-bed reactor (AFBR) and anaerobic expanded-bed reactor (AEBR)

In these reactors, which came on the heels of UASB, [182,364]; active biomass is grown on small, inert particles such as fine sand or alumina. These particles are kept in suspension (Fig. 7) by a rapid upward flow of the incoming wastewater [182,364,403]. Higher the rate of flow, greater is the extent of expansion of the particle bed. On this basis the reactor is called a fluidized-bed reactor (> 25–300% expansion) [202] or an expanded-bed reactor (15–25% expansion) [157].

These reactors run well on feed that is soluble, or contains suspended material that is easily biodegradable like whey, whey permeate, black liquor condensate, etc. [364].

AFBR and AEBR can also treat raw sewage at a fairly high loading rate with high COD removal [182]. Illustrative examples of typical capacities of these digesters, types of wastes they can handle, loading rates, HRTs maintained, etc., are presented in Table 9.

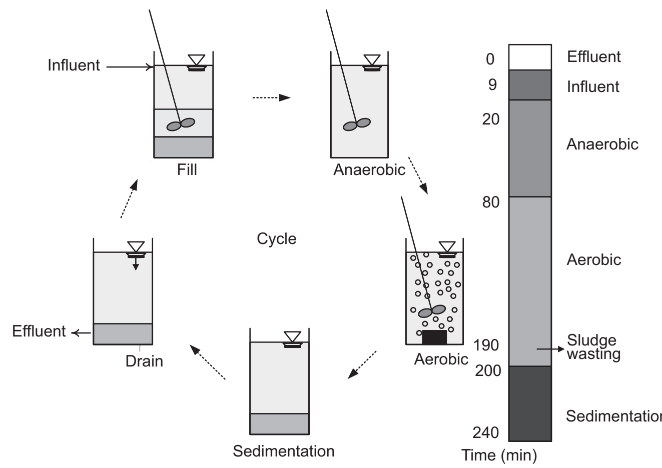

Fig. 8. A typical SBR cycle [286].

Table 9
Wastewater treatment by expanded-bed and fluidized-bed reactors: illustrative examples.

Type of waste	Waste strength (g/l)[a]	Suspended solids (g/l)	Reactor size (l)	Reactor temperature (°C)	Loading rate (g/d)	Conversion (%)	References
Liquor from heat-treated sewage digester sludge	4–9	–	7	35	4.2–26.5	48–75	[53]
Whey	10	–	0.5	35	10–20	87	[363]
Raw sewage	0.15–0.3	< 0.1	1	20	0.65–35	0–85	[182]
Synthetic waste with cellulose	0.3–1.8	–	0.5	30	2	74–83	[269]
-do-	0.3–1.8	–	0.5	30	5	75–83	-do-
-do-	0.3–1.8	–	0.5	30	8	40–83	-do-
Thermal sludge conditioning liquor	11	< 0.5	29	35	0–30	52	[156]
Whey	55[a]	–	50	35	17–37	65–84	[168]
Whey permeate	10–30	–	60	30–35	8–24	80–90	[233]
Black liquor condensate	1.4	–	1	22	10	80	[278]
Synthetic refining wastewater	9.7	–	–	36	19.7[b]	72	[361]
Synthetic wastewater	1.1	–	–	35	4.5 (VS)	25–93	[382]
Synthetic waste with glucose	–	18.6 mg	–	35	2.4–3.6[b]	–	[431]
Wine industry waste	7.8[c]	–	–	35	6.20[b]	91.1	[94]
Brewery wastewater	–	–	–	25	27–30[b]	85	[235]
Brewery wastewater	40	–	1	37	–	95	[67]
Synthetic wastewater	–	–	–	–	30	83–91	[314]
Pickled-plum effluent	–	–	–	–	11.1	84.6	[369]
Ice cream wastewater	–	–	–	35	15.6	94.4	[65]

Results are based on COD, BOD, or TVS. Loading rates given are mostly the highest reported or achievable. Loading rates and conversions are given in COD, BOD, or TVS depending on units used for waste strength.

[a] Measured as COD.
[b] Loading rate expressed in kg COD m^{-3} d^{-1}.
[c] kg COD m^{-3}.

5.5. Anaerobic sequencing batch reactor (ASBR)

Sequencing batch reactor (SBR) has been in vogue since over 90 years but is has gained increasing popularity in recent years with the growing evidence that SBR enables better process control and higher process efficiency than many continuous systems [118,347,360]. Increasing power and decreasing costs of computer-based controls has made its use more easy and more effective than was possible earlier.

SBR is a variation of the activated-sludge process, with the difference that in SBR all of the treatment steps and processes occur in a single basin, or tank, whereas conventional ASP requires more than one basin [37,413]. It can be said that an SBR is an activated sludge process designed to operate under non-steady state conditions. An SBR operates in a true batch mode with aeration and sludge settlement both occurring in the same tank. The major differences between SBR and the conventional, continuous-flow, activated sludge system is that the SBR tank carries out the functions of equalization, aeration, and sedimentation in a time sequence rather than in the conventional space sequence of continuous-flow systems. In addition, the SBR system can be designed with the ability to treat a wide range of influent volumes whereas the continuous system is based upon a fixed influent flow rate [37,316,421]. Thus, there is a degree of flexibility associated with working in a time rather than in a space sequence, which gives SBR an edge.

In its most basic from, an SBR is a tank that operates on a fill-and-draw basis. The tank is filled during a discrete period of time and then operated as a batch reactor. After desired treatment, the mixed liquor is allowed to settle and the clarified supernatant is then drawn from tank. This fill-and-draw cycle of a typical SBR is divided into five discrete time periods: Fill, React, Settle, Draw, and Idle as shown in Fig. 8. There are several types of Fill and React periods, which vary according to aeration and mixing procedures [244]. Sludge wasting may take place near the end of the React, or

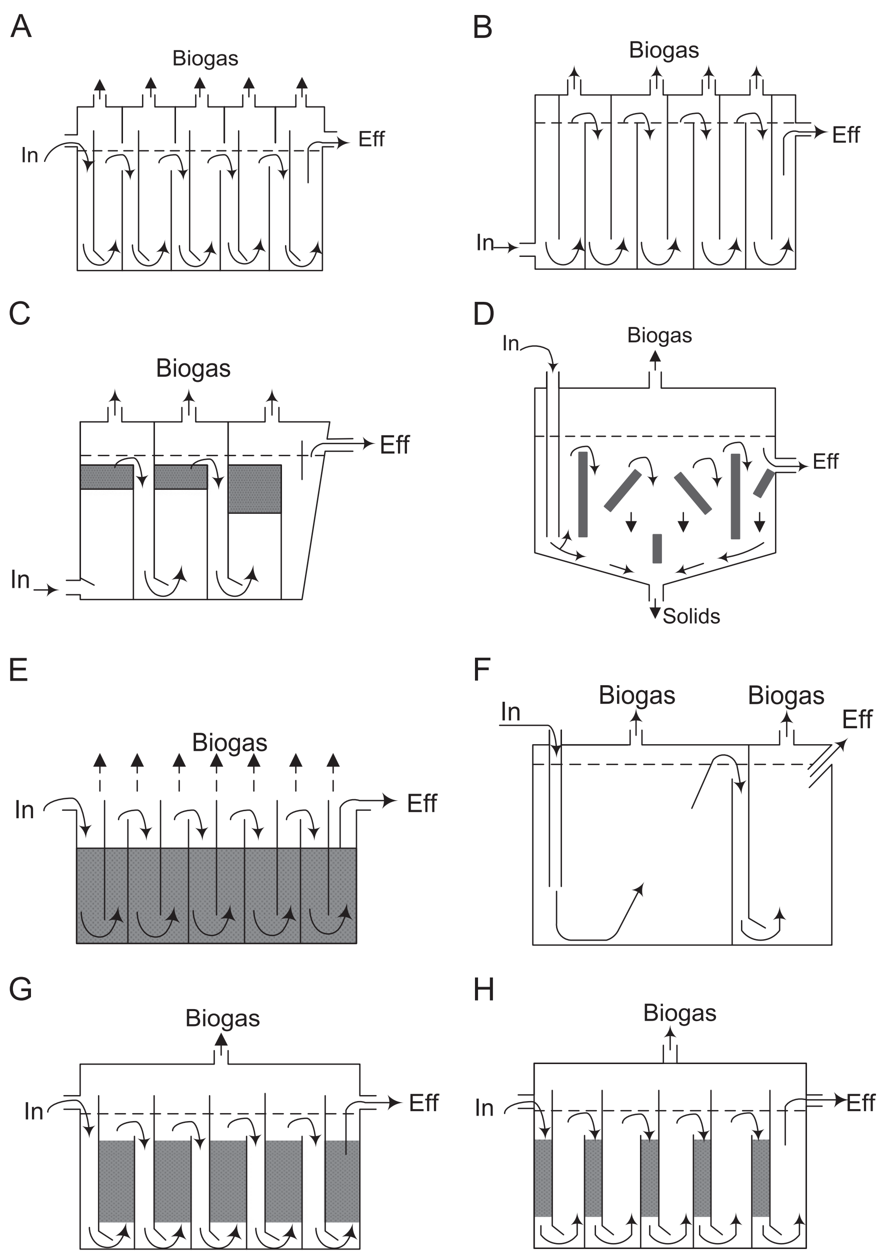

Fig. 9. The many possible ways in which anaerobic baffled reactor can be configured: (A) top fed single gas headspace, (B) top fed individual gas headspace, (C) bottom fed individual headspace, (D) slanted baffles, (E) hybrid with settling zone, (F) open top, (G) inequal compartment, (H) upflow packed baffle, (I) down theme pested baffle, (J) entire reactor. Key: In=influent, Eff=effluent (shaded areas represent random packing).

during Settle, Draw, or Idle. Central to SBR design remains the use of a single tank for multiple aspects of wastewater treatment.

The main advantages of SBR technology are seen in the anaerobic sequencing batch reactor (ASBR), too, viz operational simplicity, efficient quality control of the effluent, flexibility of use and high biogas yield [347]. However, operation of an ASBR requires some type of agitation to improve transfer of the substrate to the microorganisms in the granulated biomass for anaerobic degradation [176]. The agitation is achieved by recirculating the liquid or gas phases or by mechanical stirring.

The system performance being directly related to biomass settling, self-immobilization as it occurs naturally in an ASBR is not sufficient to achieve good settleability. Hence, immobilization of biomass on inert supports has been explored to enhance biomass retention. Use of polyurethane foam reportedly achieves high organic matter removal efficiency and high solids retention, even eliminating the settling step [70,309,347]. However, it requires mixing to maintain mass transfer rates.

The technological potential of ASBR has already been assessed for several types of effluents, including the ones generated by dairies, dye and textile industries, breweries, pulp mills, tanneries petrochemical industries and other sources [70,134,264,290, 347,360,436]. Ong et al. [285] report that addition of co-substrates and nutrients to the solution of the dye Orange II in an anaerobic sequencing batch reactor (ASBR) enhanced the breakdown of the dye, effecting removal of its colour from 27% to 89%. The decrease in mixed liquor suspended solids concentration by endogenous lysis of biomass seemed to preserve a highly reducing environment in the ASBR, which apparently facilitated the reduction of the azo dye. The authors had earlier found that Orange II did not exert significant inhibitory effects on the activity of the activated sludge microorganisms [283] and a UASB–SBR combination was also effective in disintegrating Orange II [284].

Even as there is rapidly piling evidence of the versatility of ASBT, many scientific features still have to be studied to achieve better understanding of the operational aspects of this reactor [347].

5.6. Anaerobic baffled reactor (ABR)

ABR is another reactor type which was developed long back [45] but is gaining popularity in recent years. In ABR, alternating hanging and standing baffles are placed in order to compartmentalise the reactor, as well as to force the liquid flow up and down from one compartment to the next (Fig. 9A). By rearranging the baffles and flow patterns, a large verity of ABRs can be set up (Fig. 9) to suit different needs. For over two decades after its introduction, ABR had enjoyed very limited popularity but in recent years its advantages are coming to the fore. Settling in the upflow region of each compartment in ABR results in the retention of high concentrations of biomass and high performances can therefore be achieved, while overall sludge production is quite low [98]. Other advantages include higher tolerance to hydraulic and organic shock loads [144,424], longer biomass retention times and lower sludge yields compared to many other high-rate anaerobic reactors [54].

ABR – which can be perceived as a series of UASB reactors – is also being increasingly explored for the treatment of domestic sewage [60]. ABR appears to be free from the risk of clogging and sludge bed expansion which besiege other systems, such as the anaerobic filter and the conventional UASB reactor [246].

6. Third generation high-rate digesters

As experience with the ‘second generation’ high-rate anaerobic digesters grew, problems of clogging and wash-out of microbes from the digesters, inadequate mixing and settleability of the microbial granules within the reactor, and incompatibility with certain types of wastewaters were encountered. To solve these problems, attempts to modify reactor designs have been made worldwide. A large number of new digester models have evolved which are often modified forms of, or hybrids of, the second generation anaerobic reactors. Some have added features as well. How these developments have improved the system capability is reflected in Fig. 10

Interestingly more advancements in high-rate anaerobic reactor technology have revolved round UASB than any other second generation high-rate anaerobic reactor, making it by far the most widely used of all anaerobic digestion processes [208,220,307]. In an assessment of the state-of-the-art by van Lier [404], as much as 90% of high-rate anaerobic reactors in use are seen to be either conventional UASB reactors, or their advanced versions. Just one

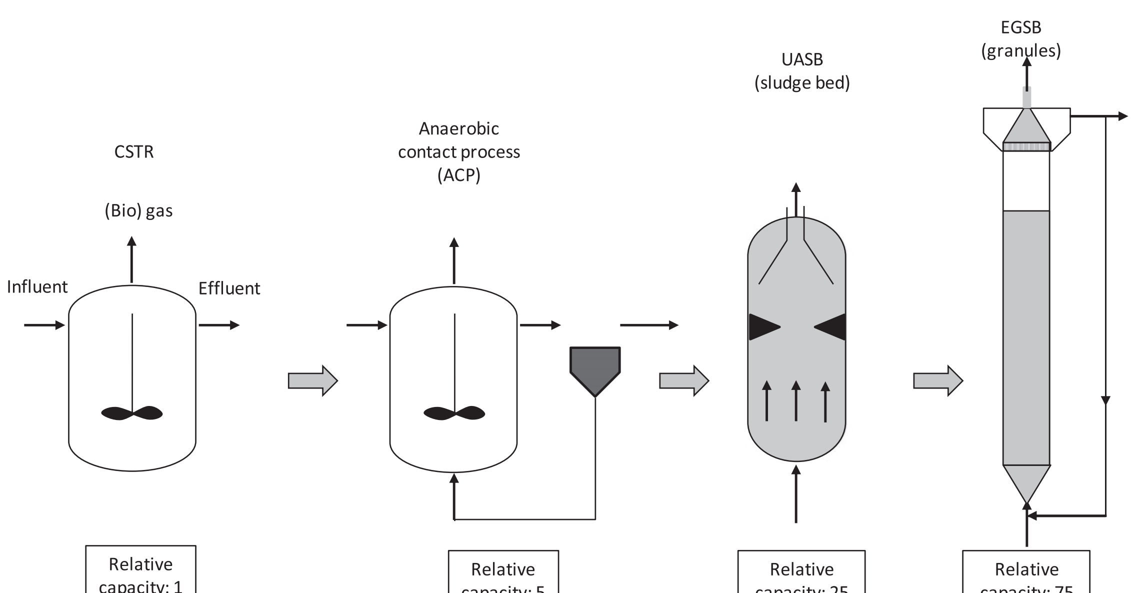

Fig. 10. Evolution of high-rate anaerobic digestion technology from the ‘first generation’ digesters (CSTR and ACP) to the ‘second’ and ‘third’ generation digesters represented by UASB and EGSB, respectively. There has been a 75-fold increase in process efficiency, in terms of treatment achieved per unit reactor volume [404].

variant of the UASB – the expanded granular sludge bed (EGSB) reactor – together with the UASB account for 72% of all anaerobic reactors presently in operation across the world [43]. Advancements have occurred in other first and second generation high-rate reactors, too, but not as spectacularly as the advancements in the UASB technology. As a result, the market share of the former has not risen with time; it rather has declined. For example the share of CSTR has declined from 7% to 4% and that of AF from 6% to 1% between 1981 and 2002 [404].

Presented below are examples of the 'third generation' high-rate anaerobic reactors.

6.1. Reactors based on advancements in the conventional UASB reactor technology

6.1.1. The expanded granular sludge blanket (EGSB) reactor

Expanded granular sludge blanket (EGSB) reactor is a variant of the UASB reactor with modified hydrodynamics (Fig. 11). It was also introduced by Lettinga and co-workers [191,229,310] to treat low strength soluble and complex wastewaters. It has by now become the second most widely used of all high-rate anaerobic digesters, after the conventional UASB [404]. It relies on: (i) exclusive use of granular sludge, (ii) operation under conditions of a slight bed expansion, and, particularly, (iii) the expectation that granules shall remain stable and will smoothly augment their biofilms [225].

The EGSB is distinguished from UASB by its ability to (i) accommodate very high organic and hydraulic loadings, (ii) treat very low-strength (COD < 150 mg/l) to high-strength wastewaters, (iii) be feasible for acidified wastewaters under psychrophilic conditions (4–10 °C), and (iv) be capable of treating wastewaters containing lipids and toxic/inhibitory compounds like formaldehyde and lauric acid [225,427]. A higher superficial velocity of 4–10 m/h is characteristic of the EGSB reactor, which is achieved by relatively greater height-to-diameter ratio of the reactor or by the recirculation of effluent (or both). The higher superficial velocity provides better hydraulic mixing and reduces the dead volumes inside the reactor. It also improves the contact between substrate and sludge and consequently improves the biodegradation of substrate by improving the diffusion of substrate from the bulk liquid to the liquid–granule interface [83].

The EGSB reactor has been widely applied for large-scale treatment of low strength as well as medium to high strength wastewater [427,443]. It also has unusually high adaptability to operating temperatures and functions well even at temperature down to10 °C [228]. In the UASB the upflow velocity is low which precludes effluent recirculation. It leads to the accumulation of toxic substances at the influent portion of the reactor and many result in process failure. In EGSB reactor the recirculation of effluent keeps diluting the reactor contents making it possible to treat wastewaters containing compounds such as tannin, phenol and phthalate which UASB cannot handle [173,443].

Even as EGSB can handle lower-strength wastewaters than efficiently possible by a UASB, it can also handle much stronger wastes – at organic loadings of up to 35 kg COD m^{-3} d^{-1} – whereas a UASB can fail at organic loading rates above 5 kg COD m^{-3} d^{-1} [333].

Due to higher applied superficial velocity, entrapment and hydrolysis of coarse suspended particles and colloids do not occur efficiently in an EGSB reactor. It limits the application of EGSB to essentially soluble wastewaters.

6.1.2. Internal circulation (IC) reactor

Next to EGSB, the internal circulation (IC) reactor is the most widely used of all UASB variants [404].

An IC reactor (Fig. 12) is in effect two UASB reactors working in tandem. It possesses the advantages of an anaerobic fluidized bed reactor (AFBR) as well as a UASB reactor [409]. Separation of biogas at two different stages and internal effluent circulation are the special features of this reactor. The latter feature is achieved by the biogas produced in the bottom compartment of the reactor where dense granular sludge is present. The gas lift carries sludge and water towards the gas–liquid separator through a riser pipe. The gas then leaves the system and the sludge/water mixer flows down to the bottom compartment through a downer pipe resulting in an internal circulation [188]. The biodegradation of the substrate predominantly occurs in the bottom compartment and the biogas along with recirculation flow and influent flow maintains the dense sludge in expanded form. Due to lower biogas production rate in the second compartment the upflow velocity is

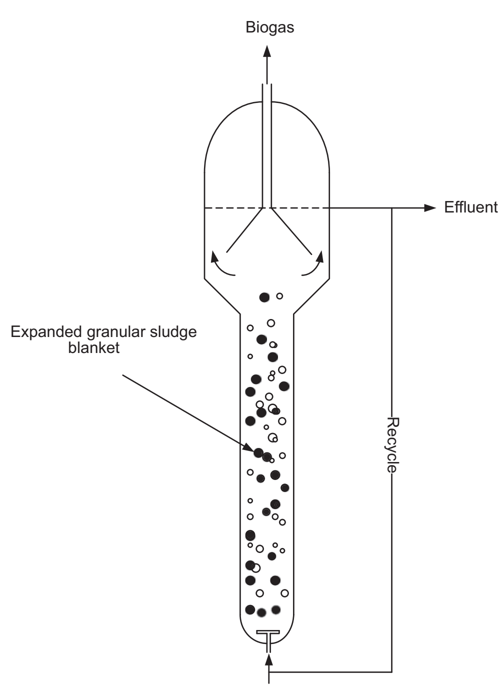

Fig. 11. The expanded granular sludge blanket (EGSB) reactor.

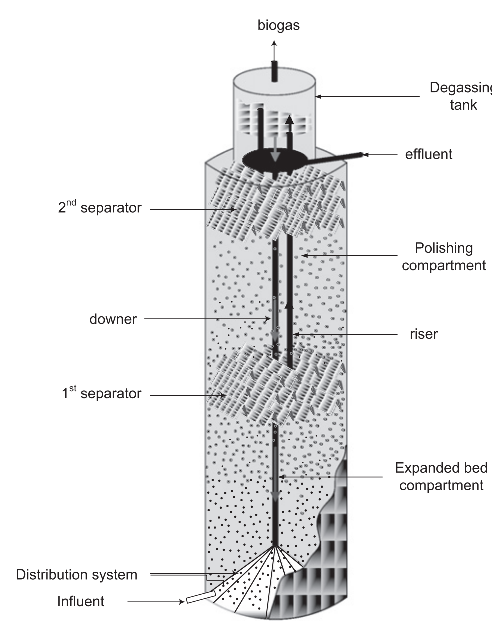

Fig. 12. The internal circulation (IC) reactor.

also lesser which enables effective separation of biomass from the effluent [112].

Thanks to the large height to diameter (H/D) ratio and effluent recirculation, a very high upflow velocity – 8–20 times higher than in conventional UASB reactors – is maintained in the first compartment of the reactor [294]. Since the IC system can handle higher upflow liquid and gas velocities compared to UASB and EGSB reactors, it can successfully treat low strength wastewaters at shorter hydraulic retention times and higher strength wastewater at higher volumetric loading rates than EGSB can [228]. It has found wide-application in agro-industrial wastewater treatment such as from dairy, food, and brewery units, ranging in strength from 1000 to 23000 mg COD l^{-1} with a hydraulic loading rate of up to 35 kg COD m^{-3} d^{-1} [112].

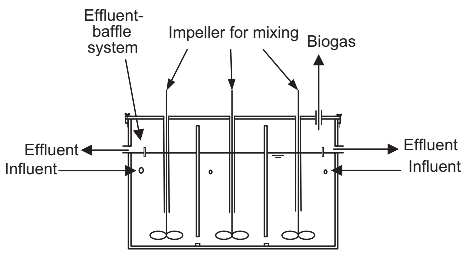

Fig. 13. Anaerobic migrating blanket reactor (AMBR) [41].

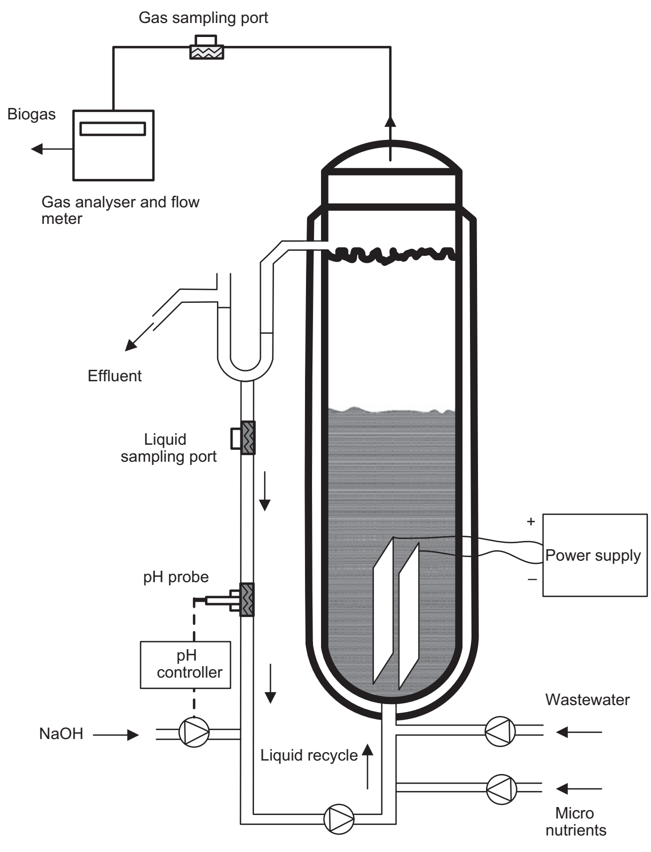

Fig. 14. Electrolysis enhanced anaerobic digestion (EEAD) [372].

6.1.3. *Anaerobic migrating blanket reactor (AMBR)*

When making a comparative study of a UASB and an anaerobic sequencing batch reactor (ASBR), Angenent and Sung [41] developed the concept of a novel bioreactor which they have named AMBR (Fig. 13).

The AMBR is a continuously fed, baffled, reactor which is not dependant on elaborate gas–solids-separation and feed-distribution systems. It does not require effluent recycling, too, but needs gentle intermittent mixing to maintain sufficient contact between biomass and substrate. In the AMBR, the influent flows horizontally into one end of the reactor and the effluent leaves from the other end. Consequently, the final compartment receives the lowest substrate concentration, and the substrate utilization rate of the microbes in this compartment is low. This results in low biogas production, which enables the final compartment to serve as a kind of internal clarifier preventing biomass loss in the effluent. Due to the flow pattern and the movement of biomass along with it, there is biomass accumulation in the final compartment. To prevent it from becoming excessive, the flow is reversed periodically. When this is done, the final compartment becomes the initial compartment and the initial compartment transforms into the final compartment. To prevent sudden disintegration of biomass flocs when the flow is reversed, at least three compartments must be provided in an AMBR. The influent is fed for a short period of time into the middle compartment as well before the flow is reversed.

Using sucrose as the main component of a synthetic wastewater feeding the AMBR, Angenent and Sung [41] achieved a maximum COD loading rate of 30 g/l d at a 12-hr HRT against 21 and 18 g/l d achievable at the same HRT with UASB and ASBR, respectively. Although a carbohydrate-rich wastewater was used, no separate pre-acidification was required for the AMBR, because of high mixing intensities and wash out of acidogenic bacteria. In contrast, the absence of pre-acidification created bulking problems (caused by abundant acidogenic bacteria at the surface of granules) in a UASB reactor, operated under conditions similar to that of the AMBR.

AMBR has been explored for treating sewage [219] but it is for the treatment of industrial organics such as p-nitrophenal, nitrobenzene, and 2,4-dinitrotoleuene that AMBR has shown promise

Table 10
Performance of hybrid reactors.

Feed	Position of UASB	Position of AF	AF packing medium	Vol. of reactor (l)	HRT (d)	Temperature (°C)	Loading rate (kg COD m^3/d)	COD reduction (%)	References
Soluble sugar waste	Bottom	Top	Plastic rings	4.25	–	27	5–51[a]	93	[148]
Piggery wastewater	Bottom	Top	–	15 m^3	–	–	5	96	[381]
Swine wastewater	–	Middle	Rope matrix	–	–	–	57	0.71[b]	[240]
Slaughter-house waste	Bottom	Top	Clay rings	–	–	35	5–45[a]	96	[65]
Chemical synthesis-based pharmaceutical wastewater	Bottom	Top	Polypropylene pall rings	14	2		3	99–85	[281]

[a] gram, per litre per day.
[b] As methane yield.

Table 11
Variants of UASB developed to address specific shortcomings of UASB, and the extent of their success.

Name of the UASB variant	Distinguishing feature	Shortcomings of UASB	Typical performance range			Extent of application	Advantages	Disadvantages
			Input range	HRT	Treatment efficiency			
Expanded granular sludge bed reactor (EGSB) [111,190]	(1) Granular anaerobic sludge is used as active biomass in EGSB (2) Effluent recirculation is possible (3) Granules are partially fluidizes by effluent recycle, at an up flow velocity of 5–6 m	(1) No effluent recirculation. (2)UASB is mostly applied on medium strength industrial effluents having a COD concentration in the range of 3000–7000 mg/l	Low strength waste water (< 2000 mg/l)	5 h	85%	Up to 2008, more than 200 full scale EGSB reactors are constructed throughout the world in the range of 30–5000 m^3 volume	(1) High rate conversion of sulphate containing waste water with a treatment efficiency of 30–5000 m^3 volume (2) Effective in treating slaughter house waste water up to an OLR of 15 kg CO m^3/d with an efficiency of 65–80% (3) Improved mass transfer and biomass activity (4) Higher COD loading rates up to 25 kg COD/m^3/d	
Internal circulation reactor (IC) reactor [151–153,273]	(1) Riser and down streamer arrangement (2) It uses an internal circulation based on airlift principle, generated by the biogas produced inside the reactor	(1) Long HRT (2) Long startup period	1200–23,000 mg/l	(1) 8–24 h for high strength waste water (2) Treatment of low strength waste water is feasible at low HRT of 2.6 h	80–90%	Up to 2003,161 IC reactors were constructed throughout the world, of which 89 are in brewery and soft drink industry,33 in pulp and paper, 39 in food,9 in distillery industry and 8 in varied chemical industries	(1) High strength waste water can be treated (2) No clogging (3) High quality effluent (4) Medium and high strength waste waters can be treated at volumetric loading rates up to 35 kg COD/m^3/d	(1) Sludge addition is not flexible, which reduces efficiency (2) Problems related to start up
UASB without internal settlers [403]	No settlers are there inside the reactor					Manufactured by SANEPAR, a local sanitary authority in Brazil and it is used commonly in Brazil for treating domestic sewage	(1) Cost effective (2) Low cost of construction	Clogging due to suspended particles
UMAR (Up flow Multi stage Anaerobic Reactor) [439]	(1) Forced internal circulation (2) Improved 3 phase separation (3) Modification of IC reactor with multistages of operation	(1) Long HRT (2) Sludge addition is not flexible	Medium and high strength waste water			Only lab scale and pilot scale	(1) Improved three phase separation (2) Improved gas-liquid separation (3) Flexible sludge addition (4) High loading rates up to 30 kg COD/m^3/d can be applied for medium/ high strength waste waters	This is the modest member of UASB and requires further study
Compartmented UASB [403]	Conventional type UASB is designed as compartments to treat waste water of different characteristics						Can be used in areas with frequent changes in influent flow rate	Same as UASB
Anaerobic Migrating Blanket Reactor [42]	Continuously fed compartmented reactor in which flow is reversed. It can treat low strength waste water at low temperature conditions	(1) Loss of biomass with the effluent due to excessive bed expansion (2) Low treatability for low strength waste water	Low strength waste water	0.5 days	59%		(1) No elaborate gas–solid separation and feed distribution system (2) No accumulation of biomass in the reactor. In terms of maximum COD loading rates	Mixing is needed and hence energy consuming

Table 11 (*continued*)

Name of the UASB variant	Distinguishing feature	Shortcomings of UASB	Typical performance range			Extent of application	Advantages	Disadvantages
			Input range	HRT	Treatment efficiency			
							and specific methane production rate, AMBR is superior to UASB	
Electrolysis enhanced anaerobic digestion [372]	The anaerobic reactor equipped with electrode increases the net methane production. Successfully tested to treats both low and high strength synthetic wastewater	Low treatability for low strength waste water	Low and high strength wastewater	6–12 h	81–89%	The concept has been successfully tested at laboratory-scale for both low and high strength synthetic waste water	(1) The micro-aerobic conditions developed because of electrolytic-oxygen increased the rate of hydrolysis of organic matter thus improving COD removal efficiency and methane production (2) Electrolytic H_2 improved the combustion properties of the biogas and increased net methane production through hydrogenotrophic methanogenesis (3) H_2S concentration in biogas was significantly reduced	

when used upstream aerobic continuously stirred tank reactor [213–216,353]. The reactor combination has been shown to achieve near total removal of these organics from synthetic wastewaters in laboratory-scale reactors.

6.1.4. Electrolysis enhanced anaerobic digestion (EEAD)

Tartakovsky et al. [372] have demonstrated enhanced methane production from wastewater in laboratory-scale anaerobic reactors equipped with electrodes for water electrolysis (Fig. 14). The electrodes were installed in the reactor sludge bed and a voltage of 2.8–3.5 V was applied resulting in a continuous supply of oxygen and hydrogen. The presence of oxygen in the biogas was minimized by limiting the applied voltage. The oxygen created micro-aerobic conditions, which facilitated hydrolysis of synthetic wastewater and reduced the release of hydrogen sulphide to the biogas. A portion of the electrolytically produced hydrogen escaped to the biogas improving its combustion properties, while another part was converted to methane by hydrogenotrophic methanogens, increasing the net methane production. At a volumetric energy consumption of 0.2–0.3 Wh/l, successful treatment of both low and high strength synthetic wastewaters was demonstrated. Methane production was increased by 10–25% and reactor stability was improved in comparison to a conventional anaerobic reactor.

A summary of the distinguishing features, shortcomings, and the range and the extent of technology penetration, of the various UASB variants is presented in Tables 10 and 11.

6.2. Anaerobic hybrid reactors

6.2.1. Hybrid anaerobic filter–UASB (AF–UASB) reactor

Retention of sludge biomass has been a major problem encountered in conventional UASB reactors during the treatment of industrial wastewater, especially effluents rich in oil and grease. A modification in the gas–liquid separation was suggested by Kennedy and Guiot [199] to solve this problem. The resulting AF–UASB reactor (Fig. 15) is a hybrid with an anaerobic filter reactor positioned over a UASB reactor. It combines the treatment advantages of both an AF and a UASB. The lower part of the reactor, where suspended growth exists, acts as a buffer zone for the toxic and inhibitory compounds present in the influent such as oil, grease, phenolic compounds and tannin. The filter bed in the upper part of the reactor handles the relatively harmless,

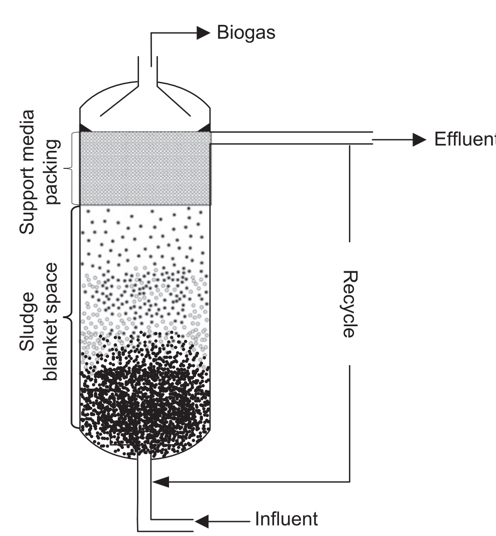

Fig. 15. Hybrid anaerobic filter-UASB (AF–UASB) reactor.

volatile fatty acid (VFA) rich, feed and allows the attachment of biomass to the bed material [44].

The AF–UASB reactor can be used for the treatment of a wide range of industrial effluents including petrochemical, phthalic, sugar industry, and phenolic wastewaters [44,46,50,304].

6.2.2. Upflow anaerobic sludge bed fixed film (UASFF) reactor

Besides requiring long time for start-up, conventional UASB reactor is less apt in treating complex wastewaters containing suspended and colloidal particles such as fats, proteins and lipids. These substances get adsorbed to the biomass surface and adversely affect the methanogenic activity by inhibiting the dispersion of substrate to the biomass and release of biogas from it. This leads to fluffing of granules and their wash out from the reactor. In an attempt to overcome this problem a fixed film was introduced inside the reactor leading to a new hybrid–upflow anaerobic sludge bed fixed film (UASFF) reactor [239]. Lo et al. [239] inserted a rope matrix as fixed film in the middle section of a UASB reactor in order to achieve advantages of both suspended and attached growth (Fig. 16). The UFF part, positioned above the UASB section retains high biomass concentration inside the reactor by preventing biomass washout [441]. Also the internal pack develops an appropriate milieu for biogranulation by re-circulating the biomass and reduces the long start-up time. It also increases the preservation of biomass by eliminating the short circuiting and improves separation of gas, solid, and liquid [274].

The UASFF reactor can treat a wide variety of wastewaters including starch, swine, slaughter house, and palm oil mill effluents. For example Borja et al. [66] achieved high COD removal efficiencies of nearly 93% at a loading rate of about 21 kg COD m^{-3} d^{-1} slaughter house wastewater.

Even as it is applicable to a wide variety of wastewaters, UASFF has proved particularly suitable for the treatment of palm oil mill effluents (POME). For concentrated POME, it achieves a COD removal efficiency of 81–97% even at high loading rates and short HRTs [274,440,441].

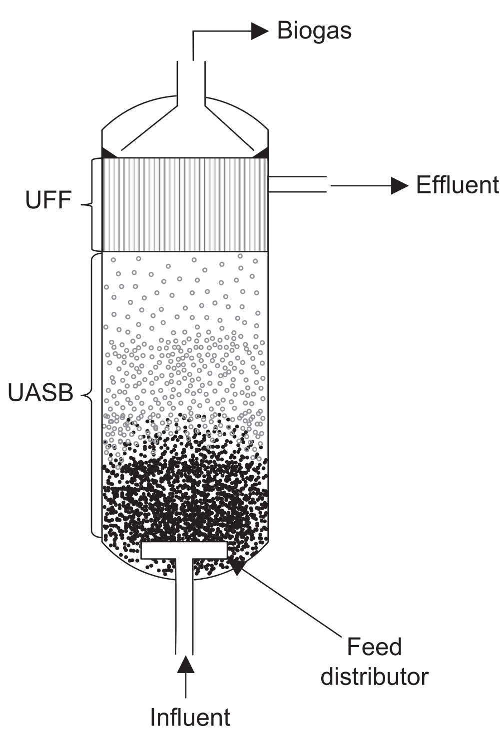

Fig. 16. Upflow anaerobic sludge bed fixed film (UASFF) reactor.

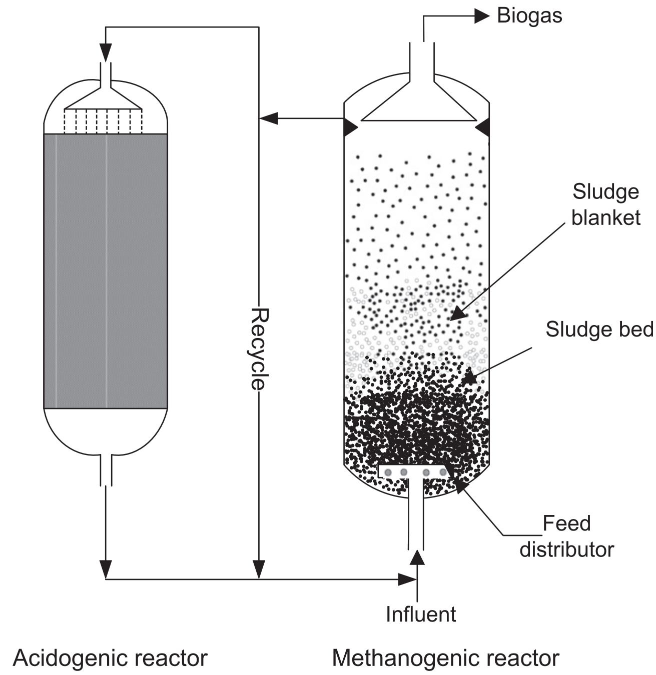

Fig. 17. Hybrid anaerobic solid–liquid (HASL)–UASB system.

6.2.3. Hybrid anaerobic solid–liquid (HASL)–UASB system

The speciality of this two-phase reactor system is that it can handle solid waste which is fed in an acidogenic reactor. The liquids which form are then fed to a UASB reactor for methanogenesis (Fig. 17) [154]. Laboratory scale and pilot scale studies on HASL–UASB system have indicated that the system is proficient in the treatment of food wastes, achieving COD removal efficiency of 70–80% and biogas of high methane content (68–70%) [154]. The performance of the acidogenic reactor was enhanced by the recirculation of the leachate.

6.2.4. Anaerobic filter and UASB-hybrid reactor trains

UASB systems have been explored for achieving anaerobic digestion of sewage at low ambient temperatures.

AUASB reactor followed by two anaerobic filters (packed with blast furnace slag) operating in parallel were able to achieve 86% removal of COD and 85% removal of total suspended solids (TSS) at ambient temperatures of 13–28 °C [80]. Another hybrid consisting of vertical reticulated polyurethane foam (RPF) sheets on top of the gas–liquid–solid separator yielded a slightly better total COD removal than that of a UASB reactor alone at the steady state (64% and 60%, respectively) in treating pre-settled domestic sewage at 13 °C [120]. When the anaerobic hybrid reactor was utilized as a post-treatment unit to an anaerobic filter, 71% removal of COD was achieved at an HRT of 12 h [121,119]. The use of RPF media at the upper part of the hybrid reactor enhanced the entrapment of colloidal COD. Sawajneh et al. [324] also achieved satisfactory COD removal with an AF–UASB combination despite the fact that the system was operated during winter.

To assist biomass attachment, a hybrid UASB-filter, in which the gas–liquid–solid separator was replaced by plastic filter rings, was used to treat domestic sludge at 10–28 °C [231]. At 10 and 14 °C, the COD and TSS removal efficiencies of the hybrid UASB-filter were lower than those of the UASB reactor by 17% and 26%, respectively, due to better solids retention in the latter. In another study [133], an upflow anaerobic fixed bed (UAFB) reactor, in which randomly packed polyethylene ring-shaped matrix pieces were fixed at the bottom half of the UASB reactor, was used to

treat domestic sludge at 15–35 °C. Decreasing the temperature from 35 to 15 °C resulted in the decrease of the COD removal efficiency by 32%. Interestingly, the maximum methane production occurred at 20 °C, yielding 7 l methane per day, which was 40% higher than that operating at 35 °C. This study showed that with a good start-up strategy (i.e. gradual lowering of the temperature from mesophilic to psychrophilic), sewage treatment with UAFB reactor is feasible in the psychrophilic temperature range [133] due to the protecting functions and the buffering mechanism provided by the UAFB reactor.

6.2.5. Anaerobic hybrid reactor with a tapered configuration

An anaerobic hybrid reactor with a tapered configuration has been introduced by Ramesh et al. [305]. According to the authors the tapered configuration (Fig. 18) can retain smaller sized biogranules more effectively than a cylindrical configuration for the same hydraulic loading rate. Trials with glucose as the sole carbon source revealed that the reactor could handle an organic loading rate up to 19.1 kg COD m^{-3} d^{-1} with a hydraulic retention time (HRT) of 0.63 h, removing around 90% of the COD. The concentration of methanogenic bacteria within the biogranules seemed to increase along the reactor height, whereas the concentration of acidogens decreased. The biogranules obtained from the upper part of the reactor had a lower diameter, lower terminal settling velocity, and more cavities than those from the lower part.

6.2.6. Anaerobic UASB–AFBR hybrid

Kumar et al. [210] used a 1 l reactor with a height-to-diameter ratio of 11 in which they maintained a superficial liquid velocity that was higher than in a typical UASB reactor but lower than in a typical AFBR. This enabled the sludge granules to remain fluidized, thereby achieving a kind of hybrid reactor which had features common to UASB as well as AFBR. The reactor achieved up to 94% COD removal at an organic loading rate of 2.08 kg COD m^{-3} d^{-1} and HRT 6 h.

In a study on the effect of operating temperatures on the microbial community profiles in a high cell density hybrid anaerobic bioreactor, Kundu et al. [211] found that the reactor operating at 37 °C showed the best performance as well as the most diverse microbial community. This was revealed by PCR-denaturing gradient gel electrophoresis analysis using 16S rRNA gene amplicons. Sequences derived from reactors operating at higher temperatures (45 and 55 °C) revealed presence of different methanogens, which had lesser diversity. This, apparently, caused a drop in the COD degradation capability of the system at those temperatures compared to 37 °C.

6.3. Reactors with phase separation

In 'multi-phase' or 'phase-separated' reactors different steps associated with the ultimate anaerobic decomposition of organic matter –especially hydrolysis, acidogenesis, and acitogenesis in one phase, and methanogenesis in another phase – are conducted separately. The aim is to improve the efficiency of both phases because each requires different types of microflora and operational conditions for optimal performance [6,11,21,27,351].

The constituent modules of phase-separated reactors vary from UASB and EGSB to hybrid reactors in accordance with the wastewater characteristics.

6.3.1. Upflow staged sludge bed (USSB) reactor

Lettinga and co-workers [405] proposed the USSB reactor (Fig. 19) to overcome the problems associated with the accumulation of intermediate products such as hydrogen and volatile fatty acids (VFAs) in conventional UASB reactors. As the problem was due to inadequate mixing, they introduced baffles along the reactor length to increase turbulence inside the reactor. The resulting USSB reactor is an approximation of a plug flow system in which different stages of degradation processes are sought to be separated from each other. The partial compartmentalization achieved by the introduction of baffles along the reactor length

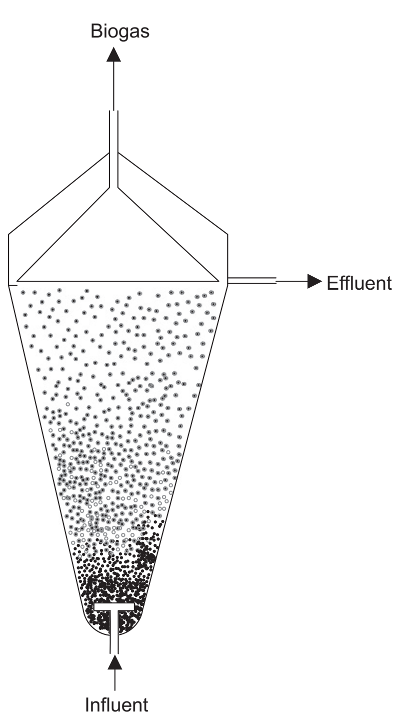

Fig. 18. Anaerobic hybrid reactor with a tapered configuration [306].

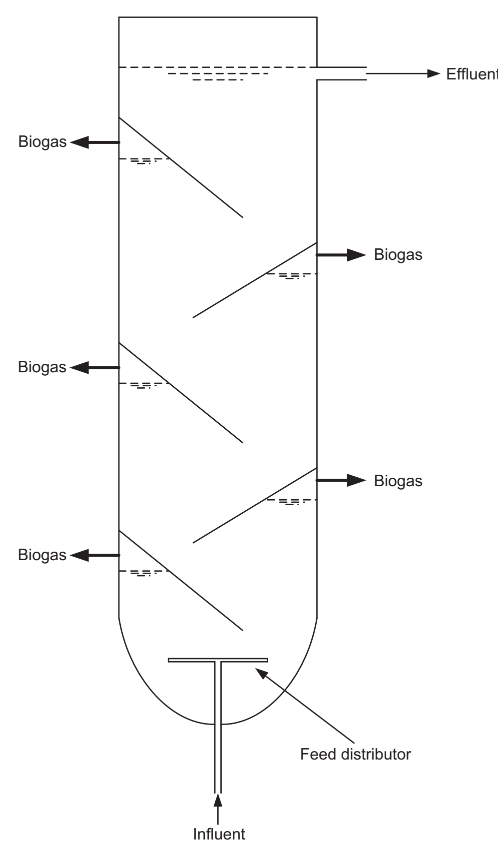

Fig. 19. Upflow staged sludge bed (USSB) Reactor.

allows easy and flexible differentiation of reactor zones. Optimal condition for hydrolysis, acidogenesis, and methanogenesis can be achieved by appropriate positioning of the baffles. This can prevent accumulation of intermediate compounds and sludge washout [335].

Lens et.al. [223] compared the performance of USSB and UASB reactors for the treatment of volatile fatty acid mixture under sulphidogenic conditions. The USSB reactor achieved a higher organic loading potential of 30 kg COD m^{-3} d^{-1} and sulphate removal of 80% compared to 20 kg COD m^{-3} d^{-1} and 74% achieved in the UASB reactor [223]. Jenicek et al. [181] achieved 99% COD removal and 90% inorganic nitrogen removal with an anaerobic–anoxic coupled configuration of USSB and aerobic fixed film [181]. The system was found to be a good alternative for the treatment of low strength, complex wastewater [335].

6.3.2. Granular bed anaerobic baffled reactor (GBABR)

This reactor (Fig. 20) combines the advantages associated with the granules, which are the mainstay in a UASB reactor, with the phase separation characteristics of an anaerobic baffled reactor (ABR) [336]. A GBABR has the following features:

i. It has compartmentalization which enhances the phase separation within the reactor.
ii. In it poor settling acidogenic sludge occurs upstream of the highly active granular methanogenic sludge zone; the latter prevents the wash out of the former from the reactor and improves process stability.
iii. In it microbial selection and zoning with acidogenic sludge are predominant in the compartments near to the inlet while methanogenic sludge dominates near the outlet portion of the reactor.

GBABR is besieged with an operational problem caused by the occurrence of back-pressure which disrupts the influent flow pattern and reduces the contact period between wastewater and biomass. Back-pressure at the start up leads to flow channeling and decreases the production of biogas by reducing contact between substrate and biomass. Excessive back-pressure leads to leakages, overflow, and reversed flow inside the reactor and results in reactor shutdown. The problem can be dampened by proper spacing of baffles inside the reactor [336].

GBABR is essentially a plug flow system with multi phase granular sludge bed characteristics which can efficiently treat domestic and industrial wastewaters. Akunna and Clark [36] found that in treating whisky wastewater with a COD of 16,000–58,000 mg/l, GBABR achieved 96–98% COD removal with 4 day HRT at a loading rate of 2.37 kg COD m^{-3} d^{-1}. The reactor also achieved a COD removal of 93–96% with high methane production rate during the treatment of brewery wastewater when operated at an organic loading rate of 2.16–13.38 kg COD m^{-3} d^{-1} [47].

6.3.3. Hydrolytic upflow anaerobic sludge blanket (HUSB) reactor

In the conventional UASB reactor, direct feeding of raw domestic sewage with high suspended solids can lead to a drop in the methanogenic activity and deformation of sludge. This

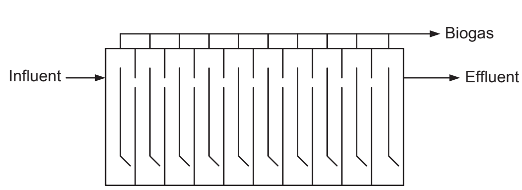

Fig. 20. The granular bed anaerobic baffled reactor.

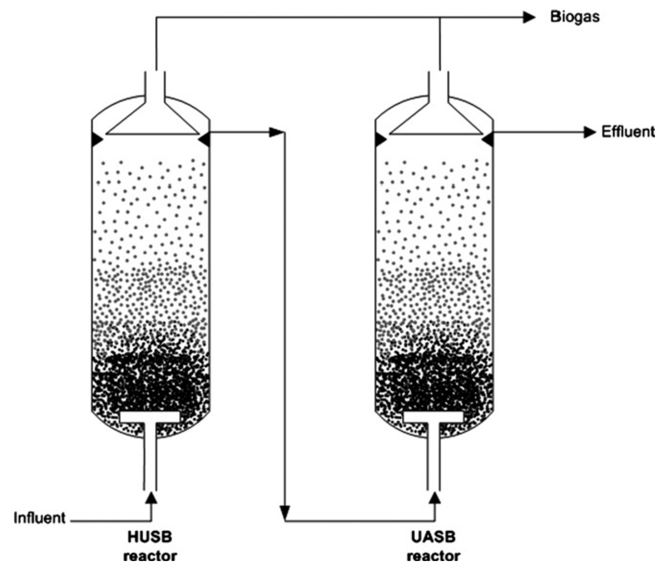

Fig. 21. Hydrolytic upflow anaerobic sludge blanket (HUSB) reactor.

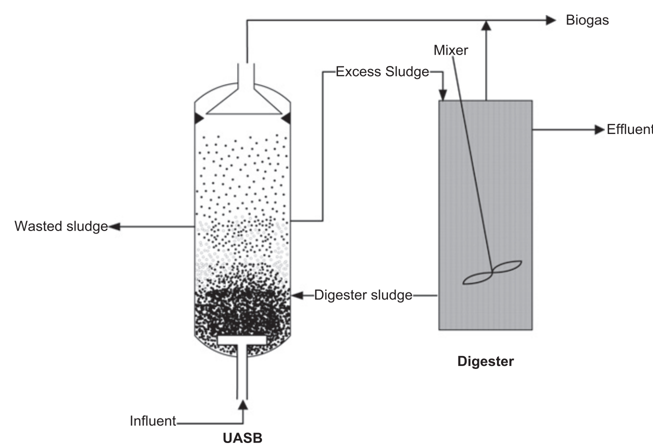

Fig. 22. UASB–sludge digester System.

makes pre-settling necessary. This situation is preempted in two stage anaerobic systems in which a hydrolytic acidogenic reactor is used in series with a methanogenic reactor (Fig. 21). The former, operating in pre-methanogenic phase, is called hydrolytic upflow anaerobic sludge blanket (HUSB) reactor because hydrolysis of complex solid particles occurs in this reactor. The volatile fatty acids (VFAs) which are formed are conveyed to methanogenic UASB reactor for anaerobic digestion leading to stabilization of waste and production of biogas.

The reactor combination hydrolyses 50–100% of the retained solids and achieves a stable performance while treating raw domestic sewage at low temperatures conditions (21–14 °C) with a COD removal of 50–60% and TSS removal of 65–85% [38].

6.3.4. UASB–sludge digester system

This system was proposed by Lettinga and Hulshoff Pol [226] in the course of attempts to achieve anaerobic treatment of sewage at low temperatures. It consists of an integrated high-loaded UASB reactor and an anaerobic sludge digester (Fig. 22). The sludge present in the UASB reactor along with the entrapped solids is conveyed to the sludge digester where it undergoes hydrolysis. The digested sludge is then re-circulated to the UASB reactor for methanogenesis. This prevents accumulation of VFAs

in the UASB reactor and improves the methanogenic activity of the microbial biomass. It is considered to be a good alternative for the treatment of raw sewage. It solves the operational problems associated with traditional anaerobic digesters such as floating of biomass and accumulation of intermediate products [226].

6.4. Integrated anaerobic-aerobic reactors: general

Effluents from anaerobic reactors may contain residual organic matter, coliforms, and reduced compounds of nitrogen and sulphur at concentrations higher than the effluent discharge standards. Hence post treatment is generally necessary before final disposal. Usually an aerobic process is incorporated downstream anaerobic process for this purpose. The aerobic process most commonly used is AASP, but a number of other options have been explored as detailed in the following sections.

When integrated in a mutually complementing fashion, anaerobic and aerobic processes can bring down the overall cost of waste treatment by almost an order of magnitude, when compared with aerobic treatment alone. In the bargain, not only higher organic matter removal efficiency achieved but there is generation of lesser amounts of sludge. Some of the benefits of using anaerobic process together with aerobic process are [73,129]:

- *Generation of relatively cleaner energy:* Anaerobic pretreatment not only removes most of the organic pollutants but also leads to the production of methane.
- *High overall treatment efficiency:* The ability of anaerobic processes in treating high-strength wastewater more efficiently then aerobic processes, and the better ability of the aerobic step in polishing the effluents produced by anaerobic reactors results in very high overall treatment efficiency. The aerobic treatment also smoothes out fluctuations in the quality of the anaerobic effluent.
- *Lesser problems of sludge disposal:* By digesting excess aerobic sludge in the anaerobic tank, the final quantity of sludge produced is minimized. The sludge is also more stable and less watery. These virtues lead to a reduction in sludge disposal cost. In addition, digestion of the aerobic sludge adds to the biogas yield.
- *Low energy consumption:* Anaerobic pretreatment acts as an influent equalization step, reducing diurnal variations of the oxygen demand and resulting in a further reduction of the required maximum aeration capacity.
- *More versatile treatment*: When volatile organics are present in the wastewater, the volatile compound is degraded in the anaerobic treatment, removing the possibility of volatilization in the aerobic treatment.

Due to these reasons it is operationally and economically advantageous to employ coupled anaerobic–aerobic processes in the treatment of high strength industrial wastewaters. Such systems have also been found to perform well for the biodegradation of chlorinated aromatic hydrocarbons [359]; sequential nitrogen removal with aerobic nitrification and anaerobic denitrification [236]; anaerobic reduction of Fe (III), and microacrophilic oxidation of Fe (II) with production of fine particles of iron hydroxide for adsorption of organic acids, phenols, ammonium ion, cyanide, radionuclides, and heavy metals [417].

Historically, the approach to the coupling of anaerobic–aerobic treatment stages has been the use of anaerobic lagoons or CSTRs with aerobic stabilization ponds [28], wetland systems [5,7,14,15] but such systems are besieged with long hydraulic retention time (HRT), low organic loading rate (OLR), as well as high requirement of land.

High-rate anaerobic–aerobic systems are much more efficient and can be used to set up treatment trains for attaining higher treatment efficiency at lesser overall costs. Oliveira and Sperling [282] compared the performance of 18 UASB reactor systems, out of which 10 plants were operating without and 8 plants with, post treatment. The assessment was in terms of compliance of the treated effluents with specified discharge standards. The post-treatment processes included aerated filter; anaerobic filter; trickling filter; dissolved air flotation unit; facultative pond and maturation pond. The authors also studied a UASB in conjunction with a shallow polishing pond and a coarse rock filter [416]. In general, the inclusion of a post-treatment step, whether it was aerobic, anaerobic, or physical–chemical, provided a substantial improvement of the effluent quality in comparison to stand-alone UASB reactor. The combined systems were able to meet more restrictive discharge standards. No sludge removal was necessary from the polishing pond or coarse rock filter when they were used downstream a UASB [416].

Efforts are also underway towards developing novel reactors in which anaerobic and aerobic treatments can be done in separate compartments of the same reactor or even together in the same compartment.

6.5. Coupling of conventional high-rate anaerobic-aerobic systems

6.5.1. UASB–aerobic activated sludge process (AASP) combination

The combination of UASB for anaerobic pretreatment, followed by AASP for aerobic post treatment, has been explored for a large variety of wastewaters which include municipal, domestic, and industrial streams [92,217,289,343,346,379,415]. Several full-scale plants are successfully operating with this combination [348,415]. A significant feature of this system is the return of the excess aerobic sludge to the UASB reactor where the solids undergo stabilization, thereby drastically reducing the sludge volume as well as making it much thicker and easier to dispose.

Sperling et al. [415] monitored and operated a pilot plant for 261 days, essentially to see the response of the system in the wake of constant or variable inflows. The plant showed consistency in COD removal, with efficiencies ranging from 69% to 84% if only the UASB reactor was used, from 43% to 56% if only the activated sludge system was used and from 85% to 93% for the overall system. The final effluent suspended solids concentration was very low, with averages ranging from 13 to 18 mg/l.

In a study by Tawfik et al. [379], on treating combined dairy and domestic wastewater with COD of about 4500 mg/l at 20 °C, at an HRT of 26 h, the UASB–AASP system was able to achieve removal efficiencies of COD, BOD, and oil/grease to the extents of 98.9%, 99.6%, and 98.9%, respectively. However, the removal of coliforms was limited; a finding which tallied with the results of Mungray and Patel [271] who have shown that even with an extensive aerobic treatment like AS, the effluent still contains significant number of total faecal coliforms, requiring disinfection.

A final COD level of 80–120 mg/l was achievable with a UASB–AASP couple as compared to 220–250 mg COD l^{-1} when only the AASP was employed in treating paper mill wastewater [224]. The combination also enabled reduction in electrical energy consumption; thus lowering operational costs.

6.5.2. UASB–aerobic fluidized bed (AFB) reactor combination

An AFB reactor, which is packed with mobile supports in which particles covered with biofilm are fluidized by the recirculation of liquid, has the advantage that in it substrate diffusion limitations are much lesser compared to stationary bed process. AFB reactors typically sport high biomass concentration, enable high OLR, have short HRT, suffer little from clogging, and possess

little external mass transfer resistance while providing large surface area for mass transfer [166,344,389]. But their applicability on a large industrial scale is marred by problems, such as difficulty in the control of the bed expansion, maintaining the thickness of the biofilm, and of the oxygen distribution system. They also entail high energy consumption due to the necessity to maintain a very high liquid recirculation ratio [222,323].

With a UASB coupled with an AFB reactor, an overall COD removal efficiency of 75% at an overall HRT of 14 h was accomplished in the treatment of a medium strength synthetic textile wastewater of 2700 mg COD l^{-1} [434]. About 45% less voluminous sludge was produced than with the AFBR alone. But the authors [434] found that if anaerobic biomass ($\sim$1 g volatile solids/l) came into the AFB reactor, it contributed to an increase in suspended solids, rather than improved COD removal, because of the fast deactivation of the anaerobes under aerobic conditions. The dead anaerobic cells diluted the specific activity of the aerobes. These findings reveal that entry of anaerobic cell mass coming out of the UASB reactor must be prevented into the AFB reactor to avoid interference in the aerobic phase by the anaerobes.

The UASB–AFB system deserves further trials owing to its potential in the biological treatment of medium strength industrial wastewaters is evidenced by its high pH tolerance, reduced sludge formation, and stable COD removal performance.

6.5.3. *Anaerobic rotating biological contactors (ARBC) and aerobic sequencing batch reactor (SBR) system*

In an anaerobic rotating biological contactor (ARBC), microorganisms get attached to a disc which is partly or totally submerged in the wastewater and rotates slowly around a horizontal axis in a covered tank through which the wastewater flows [414].

ARBC systems have the advantages of low energy requirements, short retention time, good process control, low operating costs, and the capability to handle a wide range of flows [374]. Their main disadvantage is the susceptibility of the process performance to wastewater characteristics, which limits their operational flexibility [417]. It also needs frequent maintenance of its shaft bearings and mechanical drive units.

When employing anaerobic ARBC alone for treating high-strength synthetic wastewater with COD concentrations between 3248 and 12150 mg/l^{-1}, Yeh et al. [428] noted that even though 74–82% COD removal was achieved the RBC effluent COD was still too high to meet the discharge standards.

Tawfik and coworkers [374–377,380] have carried out a series of studies on single aerobic RBC and aerobic RBCs in series for the treatment of UASB effluent. Anaerobic treatment of raw sewage in a UASB reactor followed by a single-stage RBC equipped with polystyrene disks (RBC operating at HRT of 2.5 h and OLR of 14.5 g COD m^{-3} d^{-1}) provided good COD removal (with 76 mg/l in the final effluent), and partial removals of ammonia and EC [375,380]. Tawfik and Klapwijk [374] report that aerobic RBC with polyurethane disks performs much more efficiently compared to polystyrene disks especially in terms of ammonia and EC removal. In winter, when ambient temperatures drop below 4 °C, causing the performance of UASB reactor to deteriorate, the RBC downstream can be operated with a longer HRT (i.e. >5 h) and shorter OLR (<13 g COD m^{-3} d^{-1}) to achieve desirable overall treatment.

The combination of a UASB reactor followed by two aerobic SBRs in parallel was used by De Sousa and Foresti [103] to achieve COD and total Kjeldahl nitrogen (TKN) removal efficiencies averaging 95% and 85%, respectively.

As mentioned in Section 5.5, a SBR is in essence an AASP with the difference that in AASP wastewater treatment occurs simultaneously in several units which are separated in space while in SBR the treatment occurs in the same space but in steps which are separated in time [347]. A SBR consists of one or more tanks, each capable of waste stabilization and solids separation [259]. The SBR process is flexible in handling flow variations. It needs little supervision, and can handle aerobic or anaerobic conditions in the same tank (though at different times), yet providing good contact between microorganisms and substrate. It needs small floor space, and has good treatment efficiency [203]. Due to these advantages, there is an increasing interest in the use of this process in the treatment of industrial and municipal wastewaters [134,186,237,238,264].

Lo and Liao [237,238] have explored the use of anaerobic RBC with the SBR in treating cheese whey and screened dairy manure. They report that the combination was able to achieve COD reduction of 98% and also produced substantial amounts of methane.

6.5.4. *UASB–trickling filter (TF)*

A TF is a fixed bed reactor consisting of highly permeable packing media in which aerobic condition is maintained via diffusion, forced aeration, natural convection or splashing. When wastewater is sprayed from the top in TF, it percolates towards the bottom drain, gradually forming an active fixed film of microorganisms on the surface of the packing media. The film then degrades the organic matter as the wastewater passes around it [79]. The performance of a UASB–TF combination (Fig. 23) has been found inferior to that of UASB–AASP systems in treating domestic sludge, but UASB–TF, unlike the UASB–AASP systems, can be designed with short HRTs, allowing compact treatment, low energy consumption, and low operating costs [81,101]. Several studies have shown that the return of excess aerobic sludge from the TF unit to the UASB reactor does not affect the latter's performance significantly [142,296,297].

Studies by De Almeida et al. [101] and Missagia et al. [263] suggest that when the BOD loading rate is kept at 0.4 kg BOD m^{-3} d^{-1} and the hydraulic loading rate (HLR) at 10 m^{-3} m^{-2} d^{-1} the UASB–TF system is able to produce an effluent in compliance with Brazilian local discharge standards in terms of BOD, COD, and TSS concentrations. However, the reactor duo is not able to remove ammonia beyond 13–27%, levels, possibly due to the dominant presence of heterotrophs. The use of sponges can reduce the size of TF compartments [101], and in some cases as suggested by Tandukar et al. [368], may enhance nitrification.

6.5.5. *UASB–downflow hanging sponge (DHS) reactor*

In the UASB–DHS system, proposed by Machdar et al. [242] for the treatment of sewage, the DHS reactor employs a series of polyurethene sponges as the attachment medium for the

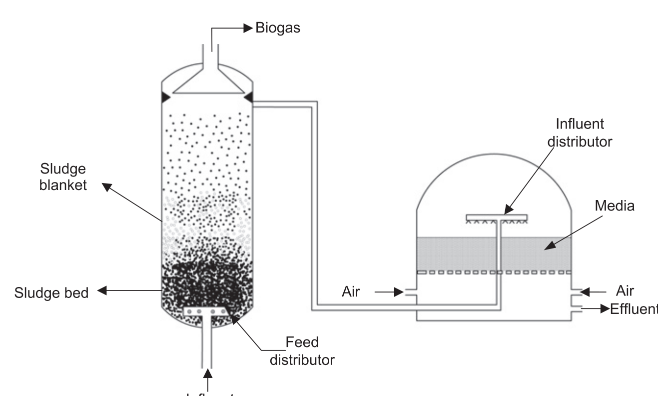

Fig. 23. UASB-trickling filter (TF).

microbial biomass (Fig. 24). Since the sponge hangs freely in air, external aeration is not needed which reduces the energy consumption. There is lesser than normal sludge production in the DHS reactor due to the wide variety of microbial groups which are supported within and on the sponge medium, thereby degrading most of the solids [388]. The DHS reactor is considered as an ideal attached growth reactor with high solids retention time (SRT), which is important for nitrification and denitrification process. Freedom from clogging, inexpensiveness of the packing material, low energy requirement, easy installation, and maintenance are some of the advantages of DHS reactors.

Three different types of DHS systems are in practice—cube, curtain, and random types. The first two types were developed by Machdar et al. [242] and the third, random type, by Tawfik et al. [378]. The cube-type DHS is a vertical string of diagonally connected sponge cubes [242]. It has limitations such as large area requirement and inappropriate feed distribution which are overcome in the curtain-type DHS. It is constructed by tiling right-triangular prism polyurethane foams on to both sides of a vertical plastic made rectangular sheet [243]. The random type DHS is a vertical column consisting of segments with randomly distributed sponge cubes. The advantages of this type of DHS over the first two types are simpler and easier construction, lower head losses, production of sludge of higher settliability, and higher specific removal rates [378]. Effluent from the UASB reactor trickles from the top of the DHS reactor and biodegradation occurs by the organism attached within and on the surface of the sponge medium, as it flows down though the reactor [388]. Pilot and full scale studies on all the three types of UASB–DHS reactors have indicated their promise in the treatment of sewage. Average COD, 5 day biological oxygen demand (BOD_5), TSS, ammonia, and faecal coliforms removal efficiencies of 90%, 98%, 94%, 96%, and 99.92%, respectively, have been achieved [378].

6.5.6. Anaerobic and aerobic fixed film bioreactors (FFBs)

Even though suspended film systems have greater tolerance to influent suspended solids and provide a lot of operational flexibility as compared to immobilized bacterial film systems, the latter do offer some advantages: a greater variation in population; less sensitivity to environmental variations (temperature, pH, and toxic substances); higher growth rate; and faster utilization of the substrate in relation to free biomass. This is attributed to physiological modification that the fixed cells undergo, due to either the increase in the local concentration of nutrients and enzymes, or the selective effect of the extracellular polymeric matrix in relation to inhibitory or toxic substances [186].

A combination of two fixed-film bioreactors (FFB), one anaerobic and the other aerobic, was evaluated by Del Pozo and Diez [104] for the treatment of poultry slaughterhouse wastewater (Fig. 25). FFB was chosen as it was expected to overcome the problem of high oil and grease content in slaughterhouse wastewater which cause scum formation in suspended biomass systems. Long corrugated PVC tubes were placed vertically as support media to avoid clogging, while the rough structure of the tubes increased their specific surface and protected the attached biomass from stress forces. The system achieved overall COD removal efficiency of 92% at OLR of 0.39 kg COD m^{-3} d^{-1}.

The FFBs were operated in a down flow manner and the aerobic effluent was recirculated to the anaerobic FFB. COD removal occurred mainly in the anaerobic FFB and this effect was accentuated when the recirculation ratio was raised from 1 to 6 as a result of the increased contribution of denitrification. There was greater COD removal in the anaerobic FFB when the volume of the aerobic FFB became smaller than the volume of the anaerobic FFB.

6.5.7. EGSB-aerobic FFB reactor combination

Zhang et al. [438] achieved an overall COD reduction of 95.6% at an OLR of 10 kg COD m^{-3} when treating palm oil mill effluent (POME) in a pilot-scale plant composed of an EGSB reactor and an aerobic FFB reactor. The anaerobic EGSB degraded a large portion of organic matter in POME with 93% COD removal while the aerobic FFB reactor broke down the remaining organic matter (22% of COD removal).

6.5.8. The HUASB–aerobic membrane reactor system

In aerobic membrane reactors (AMR), the ability of membranes to separate solids from wastewater is allied with biodegradation to achieve a very high quality effluent. AMRs offer the advantages of sharp separation of solid retention time (SRT) from HRT [26] and reduced sludge production due to endogenous respiration in long SRT [109,270,419]. The membrane-retained aqueous and particulate based enzymes which are otherwise lost in the conventional sedimentation–clarification step are also able to improve the metabolic rate in the AMR [89].The major problem with the AMR's is the propensity to fouling of the membranes. Cross-flow filtration is one of the strategies to delay the fouling.

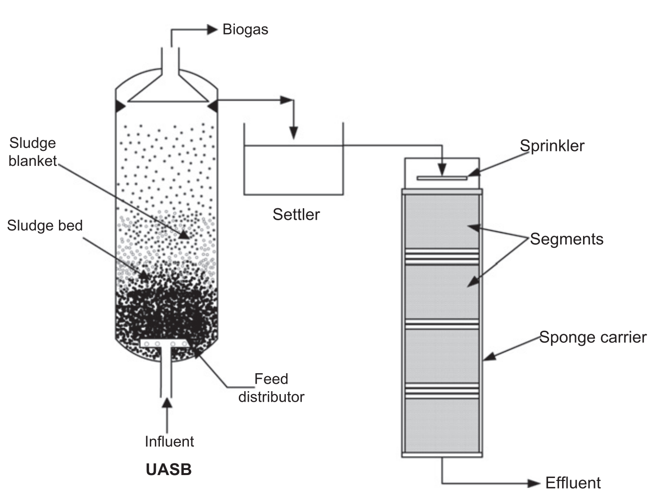

Fig. 24. UASB–downflow hanging sponge (DHS) reactor.

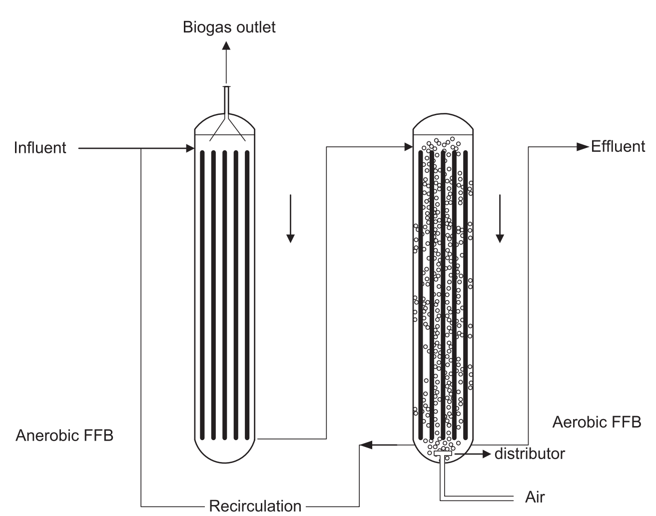

Fig. 25. Schematic diagram of anaerobic–aerobic fixed film bioreactor (FFBs) [104].

Ahn et al. [34] reported COD removal of 99% in the treatment of wastewater containing 6–14.5 kg COD m^{-3} d^{-1} by the use of an HUASB–AMR system at a relatively short HRT of 24 h. But membrane fouling was observed and the transmembrane pressure (TMP) was about 9 times higher than that of a unit AMR operated under the same conditions.

6.5.9. The precautions necessary when an aerobic system proceeds an anaerobic one

The prevention of anaerobic microorganisms from entering the aerobic reactor is crucial in the optimization of the anaerobic–aerobic system. As the aerobic reactor accepts an effluent directly from an active anaerobic digester, a significant amount of obligate anaerobes as well as facultative microorganisms can enter the aerobic reactor. They cannot quickly adapt to the aerobic conditions, and can remain as active anaerobes which can affect the microorganism demography in the aerobic reactor and lead to a mixed microbial population causing low oxygen utilization and biological activity. Moreover anaerobic cells do not contribute to COD removal in the aerobic reactor; instead they add to the carbon that must be removed aerobically. Hence it is important to minimize the ingress of anaerobic biomass into the aerobic reactor.

6.6. Integrated bioreactors with physical separation of anaerobic and aerobic zones

A combination of aerobic and anaerobic degradation pathways in a single reactor may enhance the overall degradation efficiency of the system [371]. Such reactors can be more compact, hence cost effective, than anaerobic and aerobic systems operating in separate units. But the design, operation, and process development of integrated anaerobic–aerobic bioreactors are still in its infancy and are limited to a few bench-scale studies.

6.6.1. Moving bed biofilm reactor (MBBR)

MBBR was introduced in the early 1990s [78,279]; as a reactor which tried to combine the virtues of a conventional activated sludge process and a fluidized bed reactor. In MBBR (Fig. 26) biomass is grown on small carrier elements like sponge and polyurethane foam having density less than water. The reactor contents are kept completely mixed as the carriers sporting biofilms move in the reactor due to the effect of aeration (in aerobic compartment), mechanical stirring, or the movement of gas through the water. The volume of the biofilm carrier material in an MBBR is typically up to 67% of the empty bed liquid volume (or carrier fill). Screens are installed to retain the carrier material while allowing the effluent to flow through to the next treatment step. Aerobic MBBR compartments use a diffused aeration system to uniformly distribute the biofilm carriers and meet process oxygen requirements. The carriers in denitrification MBBRs are distributed by mechanical mixers. Biofilm thickness is controlled by air flow or mechanical mixing.

The first MBBR facility became operational in early 1990 in Norway and was further developed in subsequent years, mainly in Europe and the USA [251]. By now there are more than 600 large-scale MBBR-based plants in operation in 50 different countries all over the world [253].The plants are being used for municipal and industrial wastewater treatment, aquaculture, potable water denitrification, and in roughing, secondary, tertiary, and side stream applications. MBBR installations include plants which treat wastewaters from pulp and paper industry [180], poultry processing wastewater [320], cheese making [319], refinery and slaughter house waste [183], and industrial organics [63,321]. MBBR has also been applied for biological phosphorus and nitrogen removal [167,435].

The following benefits are seen to accrue from MBBR technology:

(1) The MBBR is able to meet treatment objectives, with respect to BOD_5 and nitrogen removal, to the extent activated sludge processes can, but requires smaller reactor volumes. This translates to lesser costs [40].
(2) It achieves clarifier-independent biomass retention.
(3) It does not need any special operational cycle for biofilm thickness control.
(4) It is well-suited for retrofit installation.

An MBBR may be a single reactor or configured as several reactors-in-series. Typically, each MBBR has a length-to-width ratio (L:W) in the range 0.5:1 to 1.5:1. The robustness of MBBR is reflected from the fact that the first MBBR installed in Norway which has been inspected routinely, had shown no performance-influencing wear-and-tear on its plastic biofilm carrier wear even after 15 years of continuous operation [318].

6.6.2. Reactor with a bubble column and a draught tube

This type of reactor (Fig. 27), comprising a cylindrical bubble column with a draught tube, has been tried as a smaller and simpler substitute for two-unit anaerobic–aerobic activated sludge processes [49,160]: The inside of the draught tube is used as an aerobic zone and the annulus as an anaerobic one. The wastewater is introduced at the upper part of the annulus (anaerobic zone) and then flows with the sludge into a draught

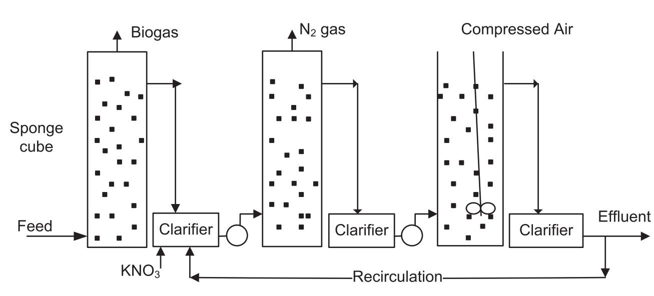

Fig. 26. Moving bed biofilm reactor (MBBR).

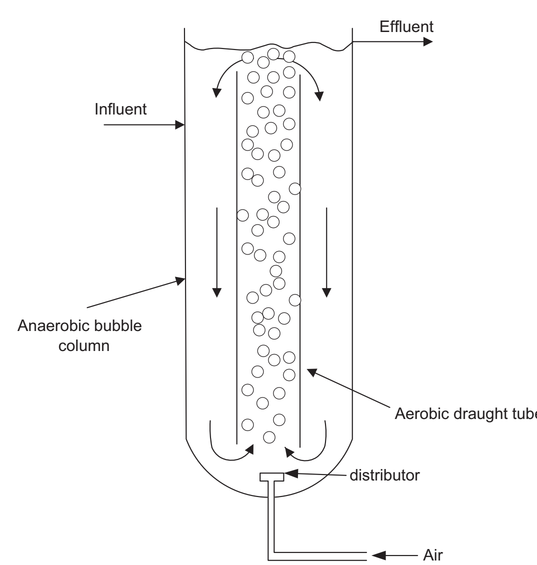

Fig. 27. Schematic diagram of the bubble column with a draught tube [160].

tube (aerobic zone) by the air-lift action. The treated effluent is withdrawn from the top of the draught tube.

The volume ratio of anaerobic and aerobic zones in the bubble column can be adjusted simply by changing the diameter of the draught tube. The circulation flow rate of mixed liquor between the two zones can be varied by changing the height of the draught tube and the flow rate of air into the draught tube. If there is too much increase in the circulation rate it will cause aerobic conditions to prevail in the annulus which is meant to be anaerobic. Hence the bubble-column treatment unit should be operated at the lowest circulation rate that can keep the sludge in suspended state.

The advantage associated with the bubble column is that no additional equipment is required to circulate the mixed liquor between aerobic and anaerobic compartments. Hano et al. [160] demonstrated that the bubble column can be used as a small scale treatment unit, since a satisfactory performance is achieved with relatively simple apparatus and operation. However, the residence time in each zone during the circulation of liquid is necessarily very short and, even if so desired it is not possible to attain longer residence times as, otherwise, the circulation flow rate shall fall below the minimum required to keep the sludge in a suspended state.

Several authors have explored rectangular airlift bubble columns installed with support material for enhanced nitrogen removal [255–257]. The support material reduces the minimum circulation flow rate. The anaerobic and aerobic regions are separated by using a partitioning plate in the rectangular airlift bubble column rather than a draft tube, as the partitioning plate is more easily inserted into the existing tank.

6.6.3. *Radial anaerobic–aerobic immobilized biomass (RAAIB) reactor*

This reactor, introduced by Garbossa et al. [135], consists of five concentric chambers (Fig. 28). The influent wastewater is fed at the top of the first chamber and flows radially from the anaerobic to the aerobic section. The second and fourth chambers are packed with polyurethane foam cubes of 10 mm sides. The second chamber is designed for anaerobic process and inoculated with anaerobic sludge while the fourth chamber is not. The third aerobic chamber contains eight porous stones which are distributed uniformly close to the bottom of the reactor and connected to a compressor to aerate and mix the wastewater. The effluent is discharged from the bottom of the fifth chamber. The polyurethane foam bed arrangement assists in the transfer of oxygen to the liquid mass in concentric chambers, and the reactor is easy to operate and control.

Sanitary wastewater with an average input COD of 345 mg/l achieved 84% treatment at HRT of 1.2–15.5 h in this reactor [135].

6.6.4. *Simultaneous aerobic–anaerobic reactor (SAAR)*

SAAR (Fig. 29) contains the features of an air lift reactor, a fluidized bed reactor, and a UASB. There is an inner cylinder and an outer cylinder in which the aerobic and the anaerobic zones are established by controlling the location of aeration, capacity of aeration, and reactor shape. The aerobic zone is formed in the inner cylinder, as air is supplied to it from the bottom. The anaerobic zone is formed in the outer cylinder due to limited oxygen transfer from the central region. The influent flows into the bottom of the bioreactor, and the effluent is withdrawn from the top. There is a decrease of dissolved oxygen concentration in the down flow zone as water flows from the inner zone to the outer zone; under oxygen-limited condition, aerobic and anaerobic processes occur simultaneously as a result of dissolved oxygen concentration gradients arising from diffusion limitations [301].

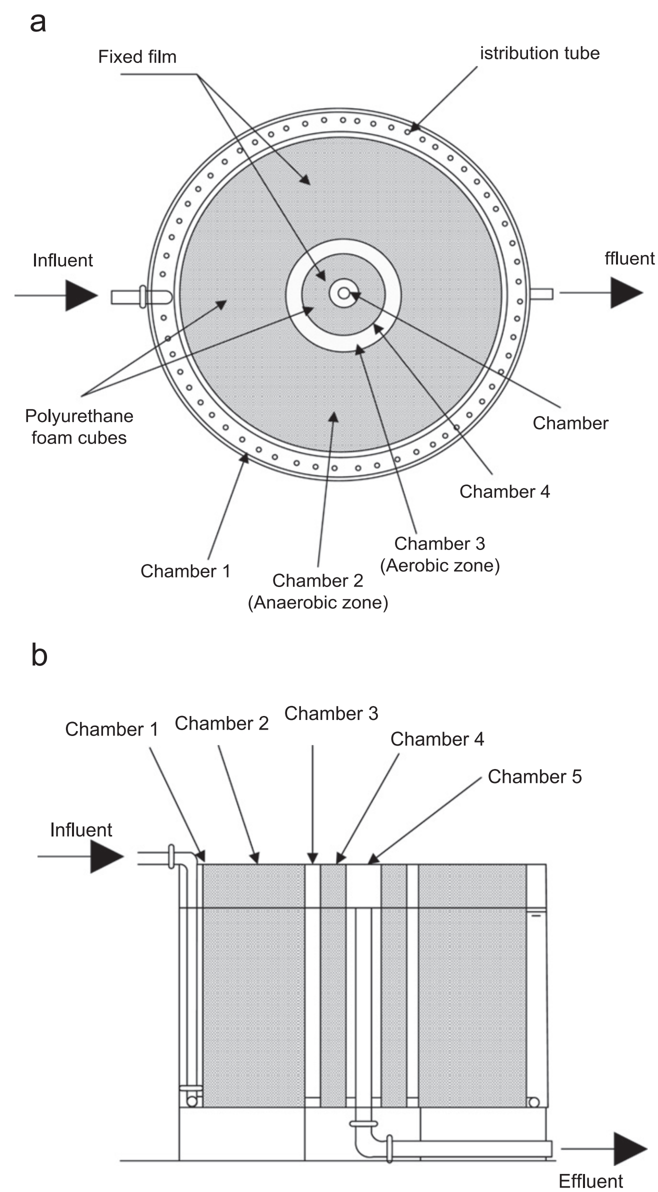

Fig. 28. Schematic diagram of the radial anaerobic–aerobic immobilized biomass (RAAIB) reactor: (a) top view; (b) side view [135].

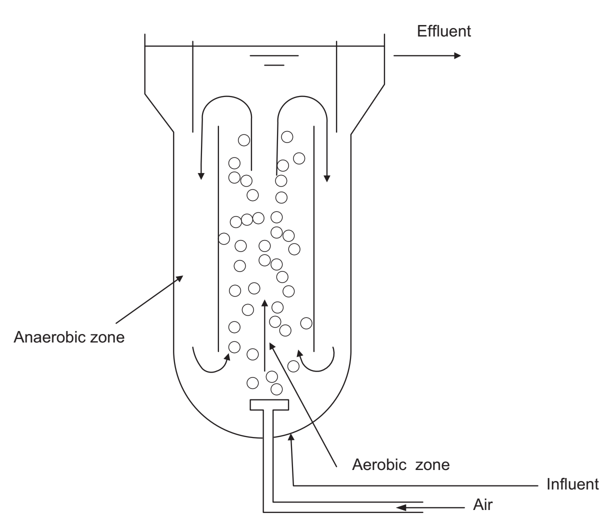

Fig. 29. Schematic diagram of the simultaneous aerobic–anaerobic reactor (SAAR) [426].

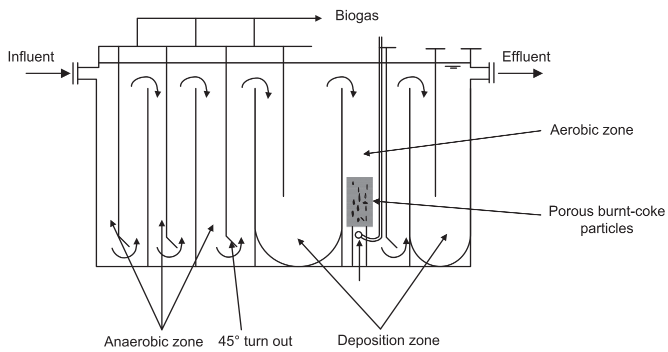

Fig. 30. Schematic diagram of the anaerobic–aerobic integrative baffled reactor (AIBR) [418].

Yang and Zhou [426] achieved 85–95% COD removal from diluted landfill leachate wastewater of COD concentration 1000–3300 mg/l. SAAR system can be superior to conventional biological process for the effective removal of organic and nitrogenous matter from landfill leachates due to its lesser space requirement and easier operation. Energy is consumed mainly for the pump and air compressor and no chemical addition appears necessary. But the efficacy is yet to be tested on a large scale.

6.6.5. *Anaerobic–aerobic integrative baffled reactor (AIBR)*

AIBR (Fig. 30) comprises three anaerobic zones, two depositions, and one aerobic zone. It is rectangular and is subdivided equally into downflow and upflow sections by a series of 5-mm thick vertical high/low baffles. Due to the 45° turn out angle, the baffles cause the wastewater to rise and then flow downwards into the reactor. The system is designed for the three phases required in anaerobic biodegradation to occur separately. The first and second anaerobic zones are designed for the hydrolysis and acitogenesis; and the third for methanogenesis. Depositions are designed for sedimentation and their main function is to separate the anaerobic and aerobic zones so that the anaerobic conditions are restricted to the anaerobic zone.

Proof of the concept studies indicate that AIBR can achieve rapid biodegradation, has low yields of sludge and good process stability [258].

6.7. *Integrated reactors without physical separation of anaerobic and aerobic zones*

These reactors are mostly in experimental stage with real-life application achieved so far in only two cases. In these reactors anaerobic and aerobic populations coexist in the same compartment. This is achieved using stacked configurations in which anaerobic conditions are maintained in the lower section while aerobic conditions are developed in the upper part. To accomplish this, aeration is done at an intermediate height within the reactor [105,127,260,266,340,371,373,437].

6.7.1. *Upflow anaerobic/aerobic fixed bed (UA/AFB) reactor*

This reactor, introduced by Moosavi et al. [266], is filled with PVC rings of 1.5 cm diameter as media and is operated in an upflow mode that consists of lower anaerobic zone and upper aerobic zone (Fig. 31). At a total HRT of 9 h (5 h for anaerobic and 4 h for aerobic) it is possible to accomplish more than 95% COD removal at OLR as high as 7.4 kg COD m^{-3} d^{-1}. This indicates the potential of UA/AFB reactor in handling high organic loads. The reactor was also able to recover immediately after receiving shock loads.

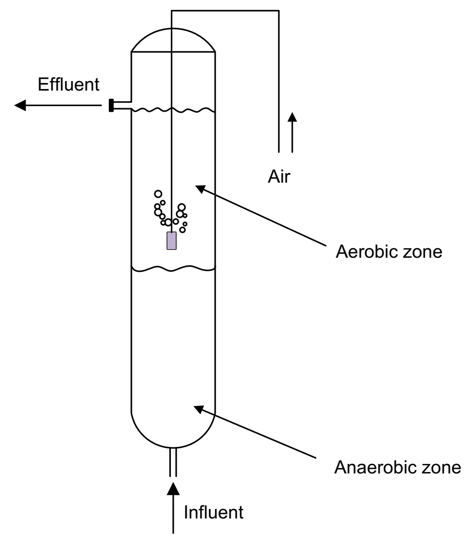

Fig. 31. Schematic diagram of combined UA/AFB integrated reactor system [266].

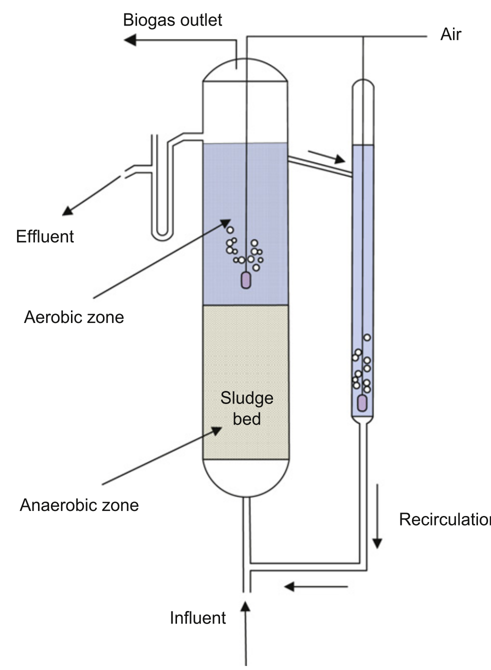

Fig. 32. Anaerobic–aerobic granular biofilm reactor (AGBR) [260,371].

6.7.2. *Anaerobic–aerobic granular biofilm reactor (AGBR)*

An AGBR (Fig. 32) is basically a UASB with either an aeration column or a sparger placed in its middle part.

AGBR has been found particularly effective in the biodegradation of various chlorinated pollutants including trichloethylene [260,371] and polychlorinated biphenyl [373]. The biodegradation of various chlorinated pollutants is apparently facilitated by the co-existence of aerobic methanotrophic and anaerobic methanogenic bacteria in a biofilm under oxygen-limited conditions.

Oxygen consumption by aerobic bacteria results in a steep oxygen gradient across the biofilm, leaving the interior with a sufficiently thick biofilm free of oxygen and thereby provides a suitable niche for the growth of anaerobic methanogenic bacteria. Simultaneously, methane produced by the methanogens combined with the presence of oxygen favours the growth of aerobic methanotrophic bacteria in the outer layer of the biomass granules. Thus, anaerobic and aerobic populations of the biofilm

co-exist closely in the same reactor system. As a result both reductive and oxidative biotransformations occur concomitantly to effect mineralization of chloroorganics [373].

Shen and Guiot [340] investigated the impact of influent dissolved O_2 on the characteristics of anaerobic granular sludge at various dissolved O_2 concentrations (0.5–8.1 mg/l) when using a laboratory-scale anaerobic–aerobic granular biofilm reactor with synthetic wastewater (75% sucrose and 25% acetate). Since the granules in a UASB are able to maintain good methanogenic activity even when dissolved O_2 is present in the upcoming fluid, It indicates that the anaerobic–aerobic granular biofilm reactors can be successfully operated to maintain both strict anaerobes and aerobes active at the same time. In the study by Shen and Guiot [340] it was seen that at elevated influent dissolved O_2 levels, the methane yield declined from 64% to 42% of influent COD while the CO_2 generation rate rose from 0.23 to 0.39 l (CO_2)/g COD, suggesting that a greater quantity of organic substrate was aerobically mineralized under high dissolved O_2 conditions. However, in spite of significant aerobic COD elimination in the coupled reactors receiving high dissolved O_2 influent, a major part of the influent COD (at least 62%) was anaerobically removed.

The downside was that a persistence of elevated levels of dissolved O_2 in the upcoming fluid resulted in fluffy bio layers on the granule surface, hampering settleability and causing some sludge washout.

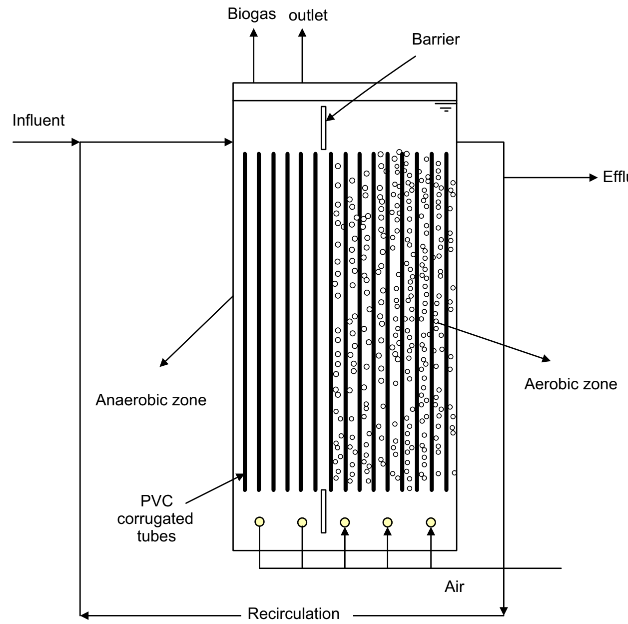

Fig. 34. Integrated anaerobic–aerobic FFB (IAFF) reactor [141].

6.7.3. *Staged anaerobic–aerobic membrane (SAM) reactor*

In SAM reactor the membrane module is submerged in the aerobic zone as shown in Fig. 33. The aeration from the diffuser in the aerobic zone of the membrane module serves three purposes: (i) providing oxygen for the biodegradation of substrates, (ii) mixing of the aerobic compartment, and (iii) producing a turbulence which contributes to membrane cleaning. Porcelain carriers are installed to prevent the blockade of the orifice between the two zones of the reactor.

SAM reactor has been employed successfully in the treatment of high strength synthetic wastewater containing high concentrations of ammonium with COD up to 10,500 mg/l and NH_4^+–N up to1220 mg/l [437]. The removal of ammonium nitrogen from the high strength synthetic wastewater was accomplished through intermittent aeration in the aerobic zone, resulting in favourable conditions for the simultaneous nitrification and denitrification. The reported COD removals exceeded 99% for OLR up to 10.08 kg COD m^{-3} d^{-1} [437]. Between 60% and 80% of COD was anaerobically biodegraded in the anaerobic zone of the reactor and converted to methane that could serve as a carbon source for the denitrification in the aerobic zone.

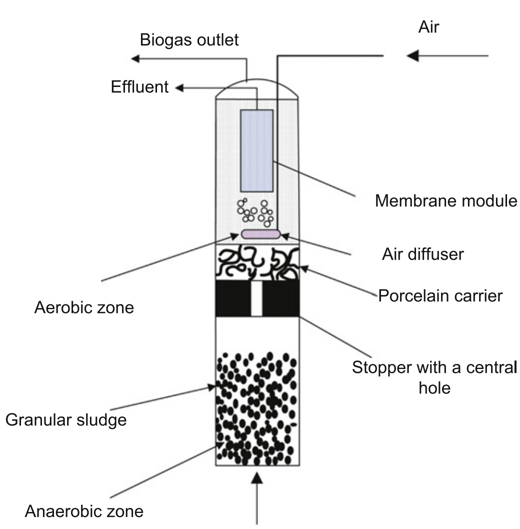

Fig. 33. Staged anaerobic–aerobic membrane (SAM) reactor [437].

6.7.4. *Integrated anaerobic–aerobic fixed-film (IAFF) reactor*

Unlike other integrated reactors which have been only tried at bench scale, IAFF has been explored at pilot-scale by Del Pozo and Diez [105] for treating slaughterhouse wastewater.

The reactor (Fig. 34) consists of vertically oriented corrugated tubes in which air is supplied using five independent membrane diffusers. The reactor is divided into two compartments, the aerobic zone (with aeration) and the anaerobic zone, without physical barriers. Wastewater enters the system from the upper part of the non-aerated region, through which it circulates downwards before being entrained up through the aerated zone due to the air-lift effect of the air injection. It then leaves the reactor from the upper part of the aerobic zone. Different anaerobic–aerobic volume ratios (V_{An}:V_{Ae}) are achieved by turning each diffuser on and off at the bottom of the reactor.

Overall organic matter removal efficiencies of 93% were achieved by Del Pozo and Diez [105] for an average OLR of 0.77 kg COD m^{-3} d^{-1} at HRT of 0.94–3.8 days. At V_{An}:V_{Ae} ratio of 3:2, most of the COD was removed through aerobic oxidation (96%); the anoxic removal accounted only for 2.6% and the methanogenic removal for at 1.2%. When the V_{An}:V_{Ae} ratio was changed to 2:3 the COD removed by methanogenesis decreased to 0.6%. The main reason for the low extension of the anaerobic process is the high mixing pattern existing in the integrated reactor. High recirculation homogenizes the aerated and non-aerated zones, maintaining dissolved oxygen concentrations of 1.4 mg/l in the non-aerated zone. To prevent this two small barriers are placed as at the top and at the bottom of the reactor seen in Fig. 34. To recover the methane without dilution by the injected air, the aerated and non-aerated regions are set in parallel rather than in series.

6.7.5. *Integrated anaerobic–aerobic fluidized bed (IAFB) reactor*

IAFB reactor has also been tested on a pilot scale for COD removal and denitrification of municipal wastewater [127]. Appreciable COD

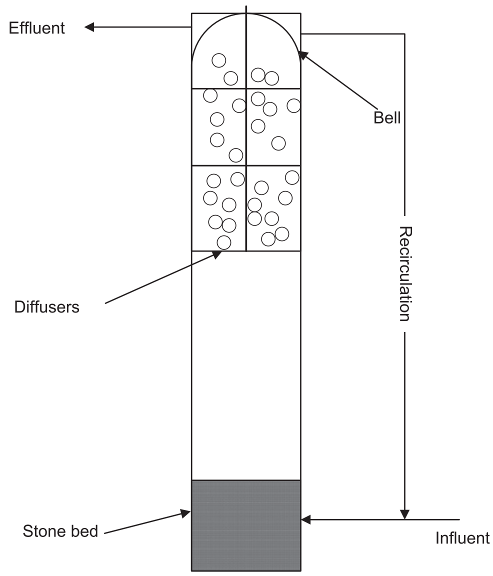

Fig. 35. Integrated anaerobic–aerobic fluidized reactor (IAFB) [127].

removal efficiencies (higher than 80%) were obtained at HRT of 24 h for an OLR of 1.2 kg COD m^{-3} d^{-1}.

IAFB reactor consists of a cylindrical fluidized bed with pulverised pumice-stone as support material. It is aerated by four cylindrical fine bubble membrane diffusers arranged in a cross shape. This system is supported by a 'bell' (seen at the top in Fig. 35) and different V_{An}:V_{Ae} ratios are achieved by varying its height in the interior of the bed.

Fdez-Polanco et al. [127] found the reactor to be robust against variations in the organic load. It had short start-up time, good recovery after being subjected to stress such as lack of aeration, and appeared amenable to possible automation using inexpensive technology. The main drawbacks were the requirement of additional pumping to maintain the support material in suspension.

6.7.6. *Anaerobic–aerobic sequencing batch reactor (AASBR)*

The ASBR system, described in Section 5.5, has been modified in the AASBR by adjusting the steps in the react cycle to provide anaerobic and aerobic phases in certain number and sequence for maximizing the rate and the extent of treatment [290].

Depending on what types of microorganisms need enrichment in a step, the desired enrichment is accomplished through the control of aeration in the AASBR system. The duration, oxygen concentration, and mixing can be altered according to the needs of the particular treatment plant. In the operation of an AASBR, pure nitrogen gas is purged in the anaerobic phase while air is supplied in the aerobic phase.

When treating textile wastewater, a slightly higher COD removal of 90% with an anaerobic/aerobic cycle of 17.5/2.5 h was achieved by Pasukphun and Vinitnantharat [290] compared to COD removal of 87% with an anaerobic/aerobic cycle of 14/6 h. It was shown that the duration of the anaerobic phase should be long enough to obtain better COD and colour removal [290]. Kapdan and Oztekin [187] obtained similar results in the treatment of synthetic textile wastewater.

In recent years anaerobic–aerobic SBRs are increasingly believed to have great potential in the treatment of high strength industrial and municipal wastewater due to their simplicity in design and operation. However, further investigations on the control of anaerobic–aerobic microbial consortia, methanogenic activity, biomass yield, and the ability to recover from shock organic loads are required.

6.8. *Integrated bioreactor based on combined anaerobic–aerobic cultures*

Combined culture refers here to the mixture of anaerobic and aerobic cultures that could survive under alternating anaerobic–aerobic conditions in the same reactor. As stated earlier, methanogenic and aerobic biological processes are often considered mutually exclusive and are operated separately as biological wastewater treatment options. Dissolved oxygen (DO) even at low levels is considered to be extremely toxic to methanogens. Nonetheless, methanogens have been found to survive for short periods in the presence of dissolved oxygen and coexist with aerobic or microaerophilic organisms in a single mixed culture. The survival of anaerobic cultures under aerobic or microaerobic conditions (i.e. DO concentration < 1 mg/l) is due to the intrinsic tolerance or formation of anaerobic niches [122]. Based on this, combined anaerobic–aerobic cultures have been investigated increasingly over the last two decades [56,57,122,136,138,139,212,429,442].

Combined cultures have been applied successfully, albeit only at the laboratory-scale so far, in the treatment of several contaminants. These include polycyclic aromatic hydrocarbons, and highly chlorinated solvents that require sequentially operated anaerobic and aerobic or anoxic reactors [56,57,138]. With free or co-immobilized cultures of anaerobes and aerobes, DO concentrations display alternating values. The oxygen gradient results in alternating conditions from aerobic to anaerobic either through the reactor content (as in packed bed or slurry reactors) or from bulk liquid to the depths of the immobilized cocultures. This leads to conditions wherein the coexistence of anaerobic and aerobic cultures becomes feasible.

For low strength municipal wastewaters treatment, combined cultures from a mixture of anaerobic granular and suspended aerobic cultures (40:60, v/v) were developed in an upflow sludge bed reactor [122]. The combined cultures in the reactor exhibited average BOD removal efficiency of 52–76% at HRT of 0.75 d. Combined cultures which were aerated every other day (i.e. alternating cycle of anaerobic to microaerobic/aerobic conditions) were considered as the optimum as compared to cultures aerated for 4 h/d or continuously. The former had higher removal efficiencies, slightly better settling characteristic and lower oxygen requirement [122].

Appreciable COD removal efficiencies (greater than 93%) were reported in a study of sucrose biotransformation under methanogenic and oxygen-limited conditions in bench-scale batch reactors seeded with a mixture containing anaerobic digester sludge and aerobic mixed liquor [442]. In addition to oxygen-limited reactors, anaerobic (methanogenic) and aerobic (dissolved oxygen greater than 2.0 mg/l) systems were operated in parallel for comparison. It was observed that the overall COD removal efficiencies for oxygen-limited cultures, strictly anaerobic cultures, and strictly aerobic cultures were comparable under the complete-mix, suspended growth conditions. The limited-aeration conditions were achieved by introducing air through a timer-actuated solenoid valve which was open for 15 s every half-hour [442].

6.9. *Membrane-based anaerobic reactor (MBAR)*

Membrane-based wastewater treatment systems have attracted great attention in recent years due to the ability of the membranes to remove a large number of chemicals and microorganisms from water in a single unit operation [185,356]. Membrane technologies such as reverse osmosis (RO), microfiltration (MF), and ultra-filtration (UF)

have been successfully used for a variety of water and wastewater treatment applications [185,267,332].

Membrane-based anaerobic reactors (MBARs) can be broadly defined as systems integrating biological degradation of waste products with membrane filtration [90]. They are proving to be effective in removing both organic and inorganic contaminants as well as biological entities from wastewater. Advantages of the MBAR include better control of biological activity, effluent that is free of bacteria and pathogens, smaller plant size, and higher organic loading rates [89].

The proof-of-concept that membrane filtration can be coupled with anaerobic treatment of wastewater was given by Grethlein [146]. The first commercially available MBAR, for high-strength whey processing wastewater treatment, was developed by Dorr-Oliver in the early 1980s and was known as the Membrane Anaerobic Reactor System (MARS) [232,362]. The MARS process was tested at pilot scale but was not applied at full scale for a long while possibly due to high membrane costs [358]. In the subsequent years extensive research in the field of membrane technology has brought down membrane costs and significantly enhanced the membrane longevity. These developments have made MBARs increasingly cost-effective.

MBARs are composed of two primary parts—the biological unit and the membrane module. The biological unit is responsible for the anaerobic treatment of wastewater and membrane is used for the physical separation of treated water from mixed liquor.

MBARs can be classified into two major groups according to their configuration. The first group, commonly known as the integrated MBAR, involves outer skin membranes that are internal to the bioreactor (Fig. 36). The second configuration is the recirculated (external) MBAR, which involves the recirculation of the mixed liquor through a membrane module that is outside the bioreactor (Fig. 37). Both inner-skin and outer-skin membranes can be used in anaerobic wastewater treatment. The emergence of less expensive and more resilient polymeric membranes along with lower pressure requirements and higher permeate fluxes have accelerated the worldwide commercial use of submerged MBARs [31,221].

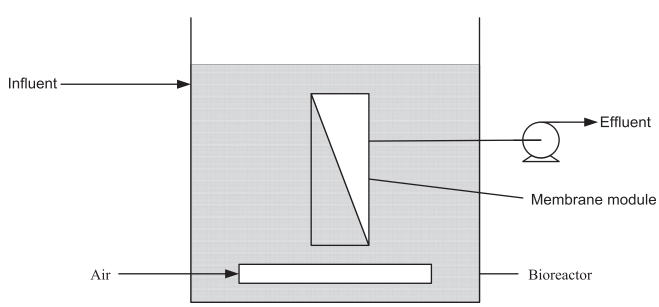

Fig. 36. Integrated (submerged) MBR [32].

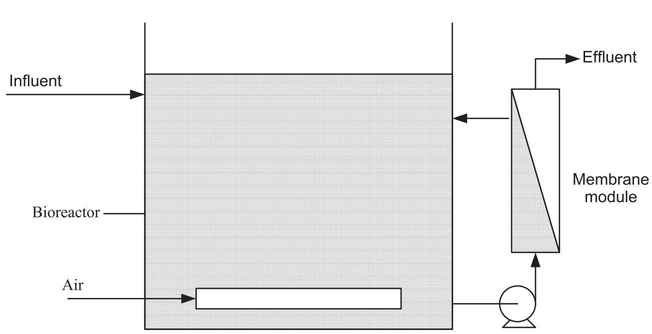

Fig. 37. Recirculated (external) MBR [32].

Several types and configurations of membranes have been used for MBAR applications [189,204,261,262,412]. These include tubular, plate and frame, rotary disk, hollow fibre, organic (polyethylene, polyethersulfone, polysulfone, polyolefin, etc.), metallic, and inorganic (ceramic) micro-filtration and ultra-filtration membranes. Criterion for the selection of membrane material and configuration, and the impact of various operating parameters on the MBAR performance have been extensively studied [33,68,247,356,396,412].

Effluents containing fats/oils and wheat starch, pulp and paper mill effluents, alcohol fermentation effluents, and night soil, which are difficult to treat with other type of anaerobic digesters, have been successfully treated in pilot-scale MBARs to the extent of COD removal exceeding 90%.

Up to 98% COD removal in treating high-strength wastewater of 5000 mg/l COD, consisting both soluble and particulate COD (cellulose) in a 1:1 ratio have also been achieved [163]. High-strength brewery wastewater, when treated using membrane technology coupled with an anaerobic reactor results in methane yield of 0.28 l/g COD with 97% COD removal, at a loading rate of 28.5 kg COD m^{-3} d^{-1} [178].

Bandara et al. [48] have explored the use of a hollow-fibre degassing membrane (DM) module attached to a UASB reactor (Fig. 38) to reduce the dissolved methane (D-CH_4) concentration in the reactor liquid and consequently enhance methane recovery. The system was particularly effective when operating temperature was low (15 °C) and, as a consequence, the D-CH_4 was high—under then conditions the DM module was able to recover 90% of CH_4.

Besides successful pilot plants, some full scale MBAR units are also operating in various parts of the world. Applications include water recycling in buildings [30,204,432], municipal wastewater treatment for small communities [69,96,124,179,385], industrial wastewater treatment [55,116,123,125,172,206,209,261,327,342,362,425], and landfill leachate treatment [218,247,311,386].

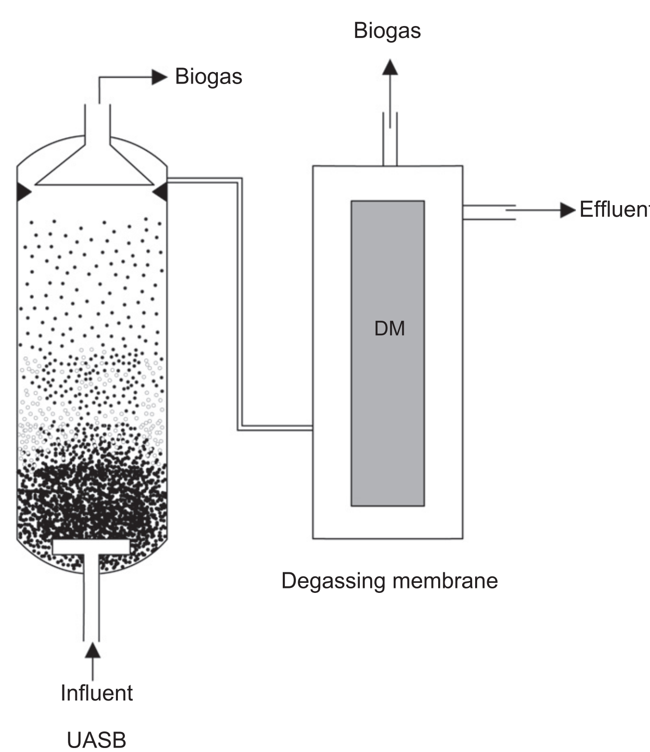

Fig. 38. Hollow-fibre degassing membrane (DM) module attached to a UASB reactor.

7. Potential for energy recovery, methane capture, and carbon credits

According to the calculations done by van Lier [404] a 25 m tall third generation anaerobic reactor of 6 m diameter is capable of treating 25 t of COD per day. Such a reactor would generate 7000 m^3 methane d^{-1} (assuming 80% CH_4 recovery based on average full-scale treatment efficiencies), with an energy equivalent of about 250 GJ/d. A modern combined heat and power (CHP) gas engine reaching 40% efficiency can convert it into 1.2 MW of electric power. The overall energy recovery could even be higher (reaching up to 60%) if all the excess heat can be used on the factory premises or in its neighbourhood. Had the same treatment been done with an aerobic process of comparable efficiency, i.e. aerobic activated sludge process (AASP), it would have required $\pm$ 1 kWh/kg of COD removed, or 1 MW of electric power. Hence the total energy benefit of using anaerobic reactor technology over the AASP is 2.2 MW. At an energy price of 0.1 €/kWh this equals about 5000 €/d.

Apart from generating energy, the system leads to certified emission reduction (CER) credits, (commonly known as carbon credits) because the energy it generates is renewable. An average coal-driven 1MW power plant emits about 20 t CO_2 d^{-1}; CER credits accrue for saving this emission. This aspect should provide a strong incentive in developing countries to start treating wastewaters using high-rate anaerobic reactors [404].

There are numerous other benefits which lead to energy saving over the life cycle if anaerobic reactors are used for wastewater treatment. The direct and indirect benefits can be itemized as follows:

1. Sludge production is lesser than in high-rate aerobic processes to the extent of up to 90%. The sludge that is produced requires much lesser energy-intensive processing and has market value.
2. Up to 90% saving in reactor volume is achievable when expanded sludge bed systems are employed—thereby proportionately reducing the capital costs and carbon footprints.
3. Advancements in the anaerobic reactor technology now enable COD concentrations varying in a very wide band to be treated—form as low as 0.001 to 35 kg/m d. This provides an opportunity to treat all biodegradable wastewater streams by anaerobic processes, thereby obviating the necessity to have aerobic 'polishing' which earlier was deemed essential.
4. Very little use of fossil fuels occurs for reactor operation, that too indirectly, saving about 1 kWh/kg COD treated.
5. There is production of about 13.5 MJ CH_4 energy/kg COD removed, giving 1.5 kWh electric output (assuming 40% electric conversion efficiency) [404].
6. Very little or no addition of chemicals is needed.
7. High-rate systems facilitate water recycling in factories (towards closed loops).
8. Crop macronutrients likeNH_4^+ and PO_4^{3-} are liberated and conserved during anaerobic treatment [404]. This provides a valuable pool of precious nutrients for use in agricultural fields.
9. For all these virtues, anaerobic digesters are relatively easier to install and operate. When using for agriculture they can be kept dormant in off-season and can be easily started up when needed.

Acknowledgements

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